Effects of Settling Pond Sediments on the Bonsall Creek Estuary: a Preliminary Study

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2002

Canadian Manuscript Report of Fisheries and Aquatic Sciences 2567

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102-03722/

Canadian Manuscript Report of

Fisheries and Aquatic Sciences 2567

2002

EFFECTS OF SETTLING POND SEDIMENTS ON THE BONSALL CREEK ESTUARY: A PRELIMINARY STUDY

by

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Cat. No. Fs 97-4/2567E ISSN 0706-6473

Correct citation for this publication:

Levings, C.D., D. Kolody, and T.F. Sutherland. 2002. Effects of settling pond sediments on the Bonsall Creek estuary: a preliminary study. Can. Manuscr. Rep. Fish. Aquat. Sci. 2567: iii + 44 p

ABSTRACT

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The Crofton Pulp and Paper Mill operates a settling pond for a water treatment plant that clarifies water diverted from the Cowichan River. The pond requires flushing of accumulated contents into the Bonsall Creek estuary. In recent years, approximately 885 t y^{-1} of sediment has been diverted from the Cowichan River to the Bonsall Creek estuary resulting in excessive sedimentation of gel-mud sediment on between 2.0 and 7.2 ha of mudflat. Anomalous patterns of sediment composition in the intertidal zone as well as visual observations by local citizens have raised concerns about potential effects on the estuarine ecosystem. The distribution and abundance of epibenthic and infaunal organisms, plant communities, and sediment size distributions were assessed in the estuary May 19-20 1998. This report summarizes the survey results and presents a preliminary analysis of the potential effects of the gel-mud from the settling pond outfall on the estuary fauna and flora.

RESUMÉ

Levings, C.D., D. Kolody, and T.F. Sutherland. 2002. Effects of settling pond sediments on the Bonsall Creek estuary: a preliminary study. Can. Manuscr. Rep. Fish. Aquat. Sci. 2567: iii + 44 p

La fabrique de pâtes et papiers de Crofton exploite un bassin de décantation pour une station de traitement des eaux qui clarifie l'eau tirée par dérivation de la rivière Cowichan. Les sédiments accumulés dans le bassin doivent être éliminés par effet de chasse dans l'estuaire du crique Bonsall. Ces dernières années, environ 885t/an de sédiments sont ainsi passés de la Cowichan à l'estuaire du Bonsall, ce qui a causé une sédimentation excessive d'un mélange gel-vase qui couvrait entre 2,0 et 7,2 ha de vasière. Les patrons inhabituels de composition des sédiments dans la zone intertidale et les observations visuelles effectuées par des citoyens de la région ont suscité des inquiétudes quant aux effets potentiels sur l'écosystème estuarien. La distribution et l'abondance des organismes épibenthiques et de la faune endogée, les communautés végétales et la distribution granulométrique du sédiment ont été évalués dans l'estuaire les 19 et 20 mai 1998. Le rapport résume les résultats du relevé et présente une analyse préliminaire des effets potentiels du mélange gel-vase provenant de l'émissaire du bassin sur la faune et la flore de l'estuaire.

A. INTRODUCTION

The Crofton Pulp and Paper Mill operates a settling pond that requires periodic flushing of sediment accumulations into the Bonsall Creek estuary (Fig. 1). The mill has diverted water from the Cowichan River since 1958, and operates the settling pond to remove sediment. Flushing the pond introduced fine sediments to the Bonsall Creek estuary at rregular intervals. Dredging of tidal channels immediately downstream from the outfall in the estuary was required, particularly in a channel used for small boat mooring, where dredging was reported to be needed twice between 1982 and 1998. (Bruce Hillaby, DFO habitat biologist, unpublished observations). Anomalous patterns of sediment composition in the intertidal zone (Campbell et al. 1982, McLaren 1996) as well as recent visual observations by Langer (1997) and local citizens have raised concerns about potential effects on the estuarine ecosystem.

During May 19-20 1998, epibenthic sled and substrate core samples were obtained in a preliminary ecological survey to investigate possible effects of the sediments discharged from the outfall. Our study focused on physical effects and did not investigate possible changes in water quality owing to chlorine and alum, which are added to the water in the settling pond. Aerial photography and vegetation mapping were also conducted to compare intertidal habitats and vegetation communities with previous data. This report summarizes the survey results, and provides an analysis of the effects of the flushing from the pond on the sediment size, abundance of benthic fauna, and sedimentation patterns in the Bonsall Creek estuary. The objectives of the analyses were as follows: 1) determine a simple model to describe the dispersion of mud from the outfall on the spatial variation of sediment grain size; 2) quantify the relationship between the sediment size and the abundance and distribution of the benthic fauna; 3) estimate sedimentation rates downstream of the outfall; 4) using empirical data, estimate the areal extent of the sediment from the outfall in the estuary.

B. METHODS

I. FIELD METHODS

A Canadian Coast Guard hovercraft based at the Vancouver International Airport provided access to the study area (Fig. 1). Some stations were sampled by foot using the hovercraft as a base because terrain and fuel supply considerations would not allow the vessel to access the area of interest. Positions of the sampling locations were obtained by differential GPS with an accuracy of about 5 m, with radar being used to locate stations sampled by foot.

The sampling stations were arrayed on a grid of five transects arranged perpendicular to the shoreline. One of the transects (AA) was in a tidal channel which received sediments from the outfall (see Fig. 1), and the other transects were located on the tidal flats to the north and west of Transect AA, including stations near the mouth

of the Chemanius River. Samples for infauna were obtained at 26 stations at low tide on May 19 1998 by pushing a metal corer (12.5 or 5.0 cm inside diameter) (coffee can) into the sediments to a depth of approximately 20 cm. These samples were not replicated. Sediment samples were then placed in plastic bags and taken to the Khoyatan Marine Lab in Cowichan Bay where they were sieved using a 1.0 mm mesh screen. Material retained on the sieve was preserved in 10% formalin with Rose Bengal.

Epibenthic samples were obtained at 15 stations, at high tide when water depth was between 50-100 cm, between approximately 2230 PST on May 19 1998 and 0130 PST on May 20 1998. The sampler described in Sibert et al. (1977) was used, pushed a distance of five meters over the sediment by personnel wearing waders. Mesh size of the net in the sampler was 44 microns. Three replicate samples were obtained at each station and preserved in 10% formalin with Rose Bengal.

During the low tide work, sediment core samples, collected for grain size analysis, were obtained by pushing a plastic core liner (PVC core 5.6 cm inside diameter; 100 cm length) by hand or driven with a sledge hammer into the substrate to the maximum possible depth. The depth that the core penetrated was measured with a tape rule. A shovel was then used to dig out sediments around the core liner tube. The tube was then capped and stored in a cooler and kept vertical until frozen in the laboratory within 24 h of the sampling.

Colour aerial photos were obtained at low tide on June 13 1998 (Selkirk Remote Sensing, Flight Line SRS 5922) to investigate vegetation communities. The vegetation in the immediate vicinity of the outfall (shown in frame 5922-24) was groundtruthed in a field survey on September 25 1998 (Precision Identification 1998). Vegetation communities in 1998 were compared by inspection of these data with a habitat map prepared of the same area in 1981 (Campbell et al. 1982).

II. LABORATORY ANALYSIS

The dominant taxa from the core sampling were identified and enumerated using a stereomicroscope (10/30 X) at the Khoyatan Marine Laboratory in Cowichan Bay. The dominant taxa were bivalve molluscs, polychaete worms, amphipods, and other crustaceans. The species composition and abundance of the organisms in the epibenthic sled samples were determined at the West Vancouver Laboratory using a Wild M-5 microscope (25 X). A subsample of sediment from the top 10 cm section of the PVC core was analyzed to determine grain size. Wet and dry sieves and pipette methods were used to determine proportions of gravel, sand, silt and clay.

III. DATA ANALYSIS

Tabulated biological data from the epibenthic sled and core samples are given in Appendix A, B and C respectively. Data on grain size of sediments in the top 10 cm of the PVC corer are given in Appendix D.

Assuming that the alteration of substrate composition is the only impact of sediment from the outfall, we made inferences in two steps: 1) a number of simple models of sediment dynamics were compared to find the best representation of the settling pond effects on the estuary's substrate composition; and 2) the relationship between the sediment composition and the species abundance across all sites was explored. Given the small sample sizes and exploratory nature of this investigation, we attempted to strike a balance between not overstating significance of potentially spurious relationships, and not overlooking qualitative trends that may be important. Because this was a preliminary survey with small sample sizes, some subjectivity was involved in interpreting the data.

An obvious effect of the outfall that has been observed in the region is the accumulation of a fine gel-mud sediment. Three indices were explored as a means of quantifying spatial variations in sediment size composition owing to the dispersion of the gel-mud (Appendix E). Since the sediments of Bonsall Creek estuary are predominantly mud and sand (McLaren 1996), it was assumed that the largest effect of the settling pond back-flushing would be an anomalous accumulation of sand, silt, and clay. The geometric mean particle size (*G*) of sediment passing through a 2 mm sieve (Appendix D) was selected as the index for measuring these effects.

A series of nested models were compared in an attempt to explain variability in the sediment size distribution. These models examined the relative importance of three very simple assertions: 1) the sediment size distribution was determined by the simple mixing of two homogeneous end members (the settling pond substrate, and the natural mudflat substrate); 2) the outfall impact was detectable for only a finite distance over the mudflat; and, 3) natural sedimentation processes dominated the region with a size gradient determined by the distance offshore. Alternative forms of assertion three that account for regional hydrodynamics and sediment loading from different sources would be more appropriate, but are beyond the scope of this study. The general form of the model is expressed:

$$G' = \begin{cases} k_1 + k_2(D_{OF}) + k_3(D_{OS}); D_{OF} < k_4 \\ k_1 + k_2(k_4) + k_3(D_{OS}); D_{OF} \geq k_4, \end{cases}$$

where G' = estimated geometric mean particle size,

D_{OF} = distance from the outfall to the sample site (km),

D_{OS} = offshore distance, the approximate distance from the sample site to the high tide shoreline in a southwest direction along the axis of the transect (ranked units where the closest site in the transect = 1, and the farthest = 5),

k_i = estimated parameters.

The following nested models were compared:

A) There is a linear relationship between the sediment size composition and the distance from the outfall (k_1, k_2 optimized; $k_3 = 0$, $k_4 = D_{OF,maximum}$).

B) There is a linear relationship between the sediment size composition and the offshore distance (k_1, k_3 optimized; $k_2 = 0$, $k_4 = D_{OF,maximum}$).

C) There is a rectilinear relationship between the sediment size composition and the distance from the outfall (k_1, k_2, k_4 optimized; $k_3 = 0$). The relationship is linear with slope k_2 up to a distance of k_4, beyond which there is no longer an effect (slope = 0).

D) There is a linear relationship between the sediment size composition and both the distance to the outfall, and the offshore distance (k_1, k_2, k_3 optimized; $k_4 = D_{OF,maximum}$).

E) There is a linear relationship between the sediment size composition and the offshore distance, and the distance to the outfall has an effect on sediment size up to a distance of k_4 (k_1, k_2, k_3, k_4 optimized).

Each of models (A-E) was optimized by minimizing the sum of squared deviations, $SSQ = (G'_i - G_i)^2$. The quality of the fit of the models was compared using the SSQ criteria penalized by P, the number of model parameters estimated: $SSQ/(N-2P)$, where N is the number of observations (smaller value of $SSQ/(N-2P)$ implies a better fit) (Hilborn and Mangel 1997) The taxa used to examine the relationship between sediment size composition and sample site location are given in Table 1.

Data on abundance of epibenthic and infauna animals are summarized graphically in Fig. 2. Data are given for all taxa from the core samples and for taxa that occurred in at least 50% of epibenthic sled samples. Relationships between sample site physical attributes (G and D_{OF}) and abundance of selected taxa important as potential fish food species were described by a correlation matrix, and linear regression models were prepared for the stronger relationships. Analyses were performed assuming that epibenthic sled and core samples were taken at the same sites, although there was some variation (see Fig. 1). Data for the mean epifauna abundance, computed from 2-3 replicates at each site were used in the correlation analysis. Table 1 lists the abbreviations for the physical and biological variables examined.

C. RESULTS AND DISCUSSION

I. RELATIONSHIPS BETWEEN DISTANCE FROM THE OUTFALL AND SEDIMENT GRAIN SIZE

The models proposed to explain variation in sediment size composition were only partially successful. Parameter estimates and goodness of fit criteria for models A-E are listed in Table 3. The sediment size composition can be explained better by the sample site distance offshore, model B, than the distance from the outfall, model A (Table 3, Fig. 2A, B). However, models B and C provide nearly equivalent fits to the data (Table 3), which suggests that the outfall may have some effect on sediment size up to the distance $k_4 = 0.8$ km. Model C fits the data very well up to a distance of 0.8 km (Fig. 2C), however, the most distant transect (E1-E5, Table 2) indicates that a broad

range of sediment sizes may be observed even in regions that are unlikely to be strongly affected by the outfall. The fullest model (E) provides the best fit to the data, even when adjusted for the number of parameters (Table 3), however, this model is only slightly better than model B. Model E also suggests that the outfall has an effect on the sediment up to a distance of 0.8 km.

These data and models were not sufficient to demonstrate any strong causal association between sample site location and sediment size. The fact that model B provided a better fit than model A suggests that the sediment dynamics are not a simple mixing of two homogeneous end members. D_{OS} was intended to represent a simple offshore gradient in hydrodynamics. Given that the Bonsall Creek estuary is located in an embayment behind the Shoal Islands (Fig. 1), it is doubtful that D_{OS} does a very good job of indexing sediment transport/stability especially in the southern region. However, the superior fit of model B does suggest that the outfall is not the only important factor affecting the sediment size distribution in the region. More detailed consideration of hydrodynamics and sediment loading from the various sources would be required to properly model the sediment distribution. As discussed by McLaren (1998) there are likely a variety of processes that affect the post-depositional movement of sediment in this estuary. In the interim, our interpretation of these results provided two preliminary assertions: 1) natural hydrodynamics are more important than the distance to the outfall for explaining sediment size over the greater part of the survey area, and 2) the outfall effect is probably not detectable beyond about 0.8 km.

II. DISTRIBUTION OF ORGANISMS RELATIVE TO DISTANCE FROM THE OUTFALL AND SEDIMENT GRAIN SIZE

Since the direct effect of the settling pond outfall on sediment distribution was difficult to quantify from the survey data, the effect on resident fauna was also problematic to describe. Obvious effects which may be attributed to an infusion of abnormally fine sediments include localized burial of organisms, interference with respiratory and feeding apparatus, and changes to the porosity of the substrate, which may affect gas exchange and burrowing activities. Because there are no data on concentrations of suspended solids in the effluent from the outfall, it was not possible to relate water quality to biological effects by referring to criteria (e.g. MELP 1995). Based on the data at hand and general ecological principles, however, it is likely that the infauna we observed in the core samples are more vulnerable to burial effects than the epifauna sampled with the epibenthic sled at high tide. Qualitative inspection of the abundance data from the core samples did not reveal any obvious trends and suggested that the organisms were rather patchy in distribution (Fig. 3). Sampling effectiveness with the core also varied between transects. Transect E was characterized by wood chips and bark beneath the surface of the substrate and this inhibited penetration by the core (can) samplers. At the other extreme the PVC corer was able to be completely pushed into the gel-like mud at the landward end of transect AA (Station AA5), near the outfall. This was the only site where the PVC corer was able to be pushed its full length (100 cm) into the sediment, suggesting that a large percentage of deposition occurs directly downstream from the outfall. Station AA5 also has higher clay (26.2 %) and silt (69.40 %) relative to other stations (Appendix D).

Abundance data of amphipods and crustaceans, important in the diet of juvenile salmonids in estuaries, (Higgs et al. 1995) demonstrated intermediate to high density at Station AA5 (closest to the outfall) relative to the other stations (Fig. 3A, B). This suggests that the mud from the outfall may not have had a strong negative impact on these taxa at the time of sampling. Other invertebrates such as polychaetes and molluscs, used as food by demersal fish in estuaries (e.g. English sole, *Pleuronectes vetulus*; Toole 1980) showed different abundance patterns. Data on polychaetes demonstrated lower abundance along all the AA stations relative to the other transects (Fig. 3C). Bivalve molluscs were not found at Station AA5, and were not observed at other stations frequently enough to justify interpretation (Fig. 3D-F). The unconsolidated nature of the silty-clay material found near AA5 would create a thick depositional layer and favour the recruitment of organisms associated with porous fine muds. Infaunal organisms using the habitat at the time of a depositional event would likely be smothered. High concentrations of sediment particles would likely lead to clogging of the filter-feeding apparatus of organisms such as bivalves and rotifers, reducing water transport rate for feeding.

The replicated epibenthic sled samples provide a different perspective on faunal distributions than the core samples, although the spatial coverage was reduced, and station AA5 was not sampled. The organisms sampled by the sled were invertebrates that moved onto the mudflats at high tide or emerged from burrows or other mudflat habitats into the water column. The crustacean taxa calanoid copepods, copepod nauplii and cirripedia nauplii demonstrated highest abundance along transect AA, while harpacticoid copepods were fairly uniformly distributed and ostracods were rare at all stations except BB4 (Fig. 4A-E). The abundance of several other taxa was highest along AA as well: dinoflagellates, rotifers, polychaete larvae, bivalves and gastropod larvae (Fig. 4F, I, K, L, M). Formanifera, nematodes and larvaceans showed intermediate abundance along transect AA (Fig. 4G, J, N). The abundance of turbellarians was low along transect AA (Fig. 4H).

The correlation matrix (Table 4) indicated weak positive relationships between *G* (sediment grain size) and all seven crustacean taxa (amphipods, unidentified crustaceans from the core sampling; calanoid copepods, harpacticoid copepods, copepod nauplii, cirripedia nauplii, and ostracods from the epibenthic sled samples). In general, lower abundance of crustacea tended to be associated with finer sediment. Assuming there was no systematic sampling bias (e.g. all taxa over- or under-estimated simultaneously), a simple binomial test can be used to demonstrate that these correlations provide very good evidence for a real relationship. If *G* has no effect on any of these taxa, then the sign of the correlation between *G* and each taxa can be considered an independent sample from a binomial population with $N = 7$, and probability of observing a positive trend = 0.5. In this case, the probability of observing seven positive relationships given $p = 0.5$ is a highly significant result, $\Pr(X = 7 \mid N = 7, p = 0.5) = 0.5^7 = 0.0078$.

An interpretation of the possible effects of increased mud in sediments on the copepod data is difficult without data on concentrations of suspended material. Most of the taxa were copepods with a wide variety of feeding mechanisms ranging from detrital

feeders (e.g. harpacticoids) to calanoids which filter feed on phytoplankton. The individual relationships between *G* and taxa abundance (Table 4) were not significant with the exception of that for calanoid copepods. However, given the number of correlations that were tested, one significant result can be expected by chance alone. The regression relationship between G and the abundance of calanoid copepods is illustrated in Fig. 5 ($R^2 = 0.31$, P = 0.030, N=15). This is not a tight relationship, and statistical significance is dependent on the 4 points of low calanoid abundance at low *G*. The shape of the relationship suggests that the sediment size effect on abundance is probably more of a threshold effect than a linear effect. It is possible that the calanoid abundance was affected by sediment distribution, as increased mud in the water column at high tide would be expected at sites where fine sediment was the dominant substrate. Increased suspended sediment has been shown to reduce the feeding rate of copepods in several studies (e.g. Butler 1995). Alternatively the relationship may reflect distance from deeper water, the main habitat of calanoid copepods, as the fine sediments were generally located at sites closer to the shoreline.

The correlation matrix (Table 4) showed that only four of the seven relationships between D_{OF} and the selected taxa are positive suggesting closer proximity to the outfall was associated with lower abundance. This was clearly not a significant result.

These results do not support a single coherent picture of the effects of the settling pond mud on the fauna of the Bonsall Creek estuary. The sediment models (A-E) suggest that factors unrelated to the outfall probably dominate the sediment size distribution over the majority of the survey area. Direct observations have indicated that there is extremely fine sediment associated with the outfall, and this effect is clearly present at Station AA5. This material has the potential to be redistributed during storm events, creating far field effects. The correlation analyses suggest that the distribution of fine sediments was weakly associated with reduced crustacean abundance at high tide, but low tide data from Station AA5 and the rest of transect AA indicate intermediate to high crustacean abundance in close proximity to the outfall. Other fauna such as polychaetes showed reduced abundance near the outfall.

At least two interpretations of these results are possible. First, these preliminary survey data may not be sufficient to adequately describe the abundance and distribution of the fauna. Second, additional unmeasured factors (e.g. nutrient loading and primary production) could be more important than sediment composition for determining abundance and distribution. In this case, the outfall may be having a negative impact on abundance of some species (e.g. calanoid copepods and polychaete worms), but the region in close proximity to the outfall may be more favourable for other taxa (e.g. amphipods) for other reasons such as increased organic material in the gel mud.

III. SEDIMENTATION RATES NEAR THE OUTFALL

In order to calculate an estimate of the sedimentation rate and loading of sediment into the affected tidal channel (landward end of transect AA5), flow and concentration data (e.g. suspended solids, mg L^{-1}) are required. These were not

initially available, so we computed an approximate deposition rate using available data on the amount of sediment flushed from the pond annually (kg y^{-1}) in recent years, and an estimate of the affected area (m^2).

According to H.A. Simons (1998) the average silt and grit load from the water flowing from the Cowichan River into the settling ponds has been about 885 tonnes y^{-1} in recent years. These were the only loadings data available until recently when daily loadings (measured once per week) became available from BC Ministry of Environment, Lands, and Parks via DFO Habitat and Enhancement Branch (Appendix F). We assumed these sediments would be deposited in the first 800 m of the tidal channel where transect AA was located, as predicted from our regression model above. From a GIS presentation of the morphology of the tidal channel (see Appendix G), we calculated that the total surface area affected in the channel would be about 2.02 ha. However, the area affected might be larger. The average depth that the PVC corer could be pushed into the sediment was about 52 cm on Transects A and AA, compared to approximately 36 cm on the other transects (Appendix D). These data indicate a deeper deposition of fine sediments on the former transects. A contouring and GIS analysis of the area where the corer could be pushed in deeper indicated about 7.2 ha of the Bonsall Creek estuary has been affected (Fig. 6).

Assuming a bulk density of 1150 kg m^{-3} for deposited gel-mud or 1500 kg m^{-3} for deposited muds (Appendix H; Sutherland et al. 1998) the predicted average sedimentation rates, or deposition heights, in the affected channel would be between approximately 3.8 and 2.9 cm y^{-1}, respectively. Because the sediments are coagulated by the addition of alum in the settling ponds (McLaren 1996), the material would likely settle in the form of a gel-mud, as confirmed by our direct observations at Station AA5. These estimated sedimentation rates are higher than those from the intertidal zone of the two BC estuaries where data are available. At the Fraser River estuary, Williams and Hamilton (1995) estimated a maximum sedimentation rate of 2.1 cm y^{-1} (range 0.3 to 2.1 cm y^{-1}) in a marsh on Sturgeon Bank. At the Squamish River estuary Pomeroy (1977) estimated an annual average rate of 1.5 cm y^{-1} in the intertidal zone.

Using the same calculations (Appendix H) with the most recent (1998-1999) annual average loadings data (Appendix F) of about 44.7 tonnes y^{-1}, the annual sedimentation rate would be approximately 0.2 cm y^{-1}. This rate is well within the natural range expected in the intertidal zone of BC estuaries (see above) and falls within the natural changes in bed elevation owing to suspension/deposition from tidal action (Whitehouse and Mitchener 1998). Even with "worst case" daily loadings (e.g. November 23 1998; 749 kg d^{-1}), daily sedimentation rates would be very low (<1 mmd^{-1}) over the estimated depositional area of the channel (800 m). However there could be very significant build up of sediments in strongly depositional areas such as bends and corners that could occur over time. In addition, the habitat in the first few m^2 downstream of the culvert would be severely affected – for example the 10 m^2 immediately below the culvert would be subjected to sedimentation of approximately 4.0 cm d^{-1} which could cause catastrophic burial of invertebrates. More research is needed on the sensitivity of invertebrates, especially larvae, to these impacts, but effects on adult invertebrates have been documented in a few local studies. For example, Chang

and Levings (1978) showed that Dungeness crab (*Cancer magister*) could not move through 20 cm of sand. Fifty percent of cockles (*Clinocardium nuttalli*) were immobilized by 10 cm of sand. Levings et al. (1978) found somewhat similar results with other species of invertebrates, in a field study on the Fraser River estuary mudflats.

IV. CHANGES IN THE COMPETENCY OF THE BONSALL CREEK ESTUARY

The equilbrium between sediment input from the Bonsall Creek watershed and its subsequent dispersal by natural hydrological and oceanographic processes have been disrupted by the introduction of sediment from the Cowichan River. In an unmodified estuary there is a dynamic balance between freshwater inflow and sediment loading from the watershed -- these factors shape the estuary (Dyer 1986) and the organisms living in it. The Bonsall Creek estuary's competency for sediment flux has been overwhelmed by sediment from the Cowichan River watershed, 885 $t\ y^{-1}$. It should also be noted that the estuary's competency has also been compromised by the construction of an agricultural dyke in the early 1900's which reduced the surface area of the estuary available for dispersion. The sediment diversion and morphological change in the estuary are likely why our study and McLaren (1996) observed unusual patterns of sediment dispersal over the Bonsall Creek mudflats. Reduced competency may also contribute to sedimentation in the affected tidal channel by moving material discharged from the settling pond outfall back into the subject tidal channel after it has been discharged seaward.

V. CHANGE IN VEGETATION COMMUNITIES

Direct comparisons of the vegetation communities adjacent to the affected channel identified by air photo interpretation of the 1998 images with the 1981 data (Campbell et al. 1982) was difficult because the latter map was not always accurate (Precision Identification 1998) (Appendix I). However Precision Identification (1998) identified a new "transition" vegetation community (Iml/Imi) (Intertidal marsh low/Intertidal marsh intermediate) that may not have been present in the 1981 data. Precision Identification (1998) speculated that a new community dominated by seashore saltgrass (*Distichlis spicata*) may have developed in response to sediment accretion, probably in the intertidal areas between tidal channels where glasswort (*Salicornia virginica*) was dominant. Both of these species are important in food webs supporting fish in British Columbia estuaries (e.g. Hillaby and Barrett 1976.)

D. CONCLUSIONS

1) Local observations indicate that the Crofton Mill settling pond outfall introduced a substantial amount of extremely fine sediment (gel mud) into a tidal channel in the Bonsall Creek estuary. These observations were confirmed by a preliminary ecological survey in 1998. Data were obtained on sediment distribution, invertebrate sampling, and vegetation community analyses using air photos and ground-truthing.

2) Simple models suggested that the sediment distribution in the greater estuary region was more consistent with an offshore size gradient than a size gradient related to proximity from the outfall. However, the best model suggested that both factors might be relevant, with an outfall effect detectable to about 0.8 km downstream. We estimated that, at a minimum, the surface area affected was about 2.02 ha. Previous sediment surveys have also indicated unusual patterns of sediment distribution in the main estuary, consistent with an inshore sediment source other than Bonsall Creek (McLaren 1996).

3) There is significant statistical evidence that fine sediments are associated with lower crustacean abundance, especially calanoid copepods sampled at high tide, possibly because these filter-feeding organisms may have been affected by suspended mud. The trend in abundance was only evident when information was combined across crustacea taxa. Data from core samples obtained at low tide in the gel mud in the immediate vicinity of the outfall showed reduced abundance of polychaete worms. However, the abundance of amphipods in the core samples was not lower, relative to other stations in the estuary. This suggests that factors in addition to the gel mud from the outfall are important to the distribution and abundance of fauna. These factors may co-vary with the natural sediment size gradient and with the adaptations of particular species. Corophiid amphipods, for example, have been shown to reduce sedimentation of previously re-suspended sediment by secreting mucous threads, which bind the particles together (Meadows et al. 1990).

4) It is likely that the high sedimentation rate of discharged material resulting in a blanket of gel mud has altered productive capacity and changed ecosystem functioning. The diversion of the sediment from the Cowichan River watershed to the Bonsall Creek estuary has changed the competency of the estuary, resulting in unusually high sedimentation rates in an affected tidal channel immediately below the outfall. Layers of gel mud were also found further seaward. In total, approximately 7.0 ha of intertidal habitat may have been affected, as estimated by the spatial distribution of fine sediment.

5) An approximation of the sedimentation rate immediately downstream from the outfall was made from engineering data on the amount of sediment diverted annually (maximum 885 t y^{-1}), the affected area of the tidal channel, and the bulk density of the settled sediment. These estimates were refined when data on daily loadings (measured once per week) were received giving information from 1998 and 1999. Even with "worst case" daily loadings (e.g. November 23 1998;

749 kg d^{-1}), daily sedimentation rates would be very low (< 1 mm d^{-1}) over the estimated depositional portion of the channel (800 m). However there could be very significant build up of sediments in strongly depositional areas such as bends and corners that could occur over time. In addition, the habitat in the first few m^2 downstream of the culvert would be severely affected – for example the 10 m^2 immediately below the culvert would be subjected to sedimentation of approximately 4.0 cm d^{-1} which could cause catastrophic burial of invertebrates. Invertebrates which are tolerant of rapid changes in sedimentation, such as some species of amphipods, may be able to cope with the rapid burial by gel mud from the outfall, and their juveniles stages are likely relatively insensitive to change in sediment. Other invertebrates such as polychaetes and bivalve molluscs rely on filter feeding in either the larval or adult stage. These organisms are not adapted to the radical and rapid change in sediment type and concentration that accompanies discharge from the outfall. In general excessive sedimentation rates are an impairment to development of natural communities of benthic animals (e.g. McGrorty and Reading 1984). Marsh plants can also be affected by excessive sedimentation. For example growth and survival of sedge (*Carex lyngbyei*) at the Squamish River estuary was reduced by spillage of silt from a dredging operation (Levings and Moody 1976). However at the higher elevations of the Bonsall River estuary where salt marsh plants are found, the gel mud from the outfall appeared to be constrained to the tidal channel AA. Salt marsh vegetation growing on the higher elevation areas on either side of the channel did not seem to be affected by the sediment. There may have been some accretion in these latter areas, accounting of the change in vegetation communities observed by Precision Identification (Appendix I).

V. ACKNOWLEDGEMENTS

Dr. Bill Austin, Khoyatan Marine Laboratories, helped with the site selection and transect location for the field survey. John Austin, Bob Holden, and Jeff Wainman assisted with the field sampling. Thanks are owing to the CG Hovercraft crew for their skill in navigation. John Austin and Perry Poon identified the organisms from the cores and epibenthic sled sample, respectively. James Hughes, working with Brad Mason, Habitat and Enhancement Branch, digitized the 1982 habitat map of the Bonsall Creek estuary and Nara Mehlenbacher conducted the subsequent GIS analyses. Sediment analyses were performed by Soilcon Ltd. Support for this study was provided by the DFO Science and Habitat and Enhancement Branches and Environment Canada. Thanks are owing to Bev Bravender, Pacific Biological Station, Dr. V. Barrie, Pacific Geoscience Centre, and to Margaret Wright and Scott Northrup, Habitat and Enhancement Branch, Nanaimo for their comments and review of the manuscript. We are very thankful for the excellent advice on document formatting, technical reviews, and proofreading by Beth Piercey.

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Table 1. List of taxa and physical indices used in the statistical analysis.

PHYSICAL INDICES

Abbreviation	Description
D_{OF}	Distance between sample site and Crofton Mill settling pond outfall (km)
D_{OS}	Distance between sample site and the high tide shoreline along transect axis (ordinal units)
G	Geometric mean particle size of sediment passing through a 2 mm sieve
%F	Percent of sediment core passing through a 2 mm sieve
%SC	Percent of fines which pass through a 0.053 mm sieve

EPIBENTHIC SLED SAMPLE TAXA

Abbreviation	Group	Order/Family/Genus	Stage
CALN	COPEPODA	Calanoida	adult
HARP	COPEPODA	Harpacticoida	adult
COPE	COPEPODA	Copepoda	nauplii
CIRN	CIRRIPEDIA	Cirripedia	nauplii
OSTR	OSTRACODA	Ostracoda	adult
DINO	DINOFLAGELLIDA	Dinoflagellida	
FORA	FORAMINIFERA	Foraminifera	
TURB	TURBELLARIA	Turbellaria	
ROTF	ROTIFERA	Rotifera	adult
NEMA	NEMATODA	Nematoda	adult
POLL	POLYCHAETA	Polychaeta	larvae
BIVL	BIVALVIA	Bivalvia	larvae
NATL	GASTROPODA	Aticidae	larvae
OIKO	LARVACEA	Oikopleuridae	adult

Table 2. Data used to parameterize models A-E. *G* – grain size (geometric mean particle size) from top of sediment cores; D_{OF} - distance from outfall (km); D_{OS}- distance from high tide shoreline.

Sample Site	*G* (mm)	D_{OF} (km)	D_{OS} (ordinal units)
AA5	0.012772	0.108043	1
AA4	0.077932	0.264106	2
AA3	0.106653	0.396158	3
AA2	0.313965	0.660264	4
AA1	0.415551	0.660264	5
A5	0.028417	0.204082	1
A4	0.047981	0.348139	2
A3	0.24137	0.480192	3
A2	0.104279	0.648259	4
A1	0.497215	0.816327	5
BB5	0.145059	0.60024	1
BB4	0.251101	0.672269	2
BB3	0.035464	0.720288	3
BB2	0.454247	0.804322	4
BB1	0.23596	0.852341	5
B5	0.43281	0.876351	1
B4	0.519653	0.792317	2
B3	0.189007	0.864346	3
B2	0.163642	0.90036	4
B1	0.607728	0.984394	5
C1	0.384085	1.320528	4
D1	0.428057	1.944778	4
E5	0.057528	3.397359	1
E4	0.128541	3.373349	2
E3	0.259731	3.32533	3
E2	0.45648	3.289316	4
E1	0.594019	3.265306	5

Table 3. Parameters and goodness of fit criteria for different models describing the sediment size composition (G) as a function of the distance from the Crofton Mill settling pond outfall (D_{OF}) and distance offshore (D_{OS}) along the transect axis. Least-squares fitting based on the observations of Table 2 ($N = 27$).

$$G' = \begin{cases} k_1 + k_2(D_{OF}) + k_3(D_{OS}); D_{OF} < k_4 \\ k_1 + k_2(k_4) + k_3(D_{OS}); D_{OF} \geq k_4, \end{cases}$$

Model	Parameters				Sums of Squares	Number of estimated parameters	Goodness of fit
	k_1	k_2	k_3	k_4	SSQ	P	SSQ/(N-2P)
A	0.2152	0.04227	*	*	0.854648	2	0.037159
B	0.0235	*	0.07897	*	0.586542	2	0.025502
C	-0.0927	0.54341	*	0.8043	0.571019	3	0.027191
D	-0.0058	0.03120	0.07626	*	0.556822	3	0.026515
E	-0.1350	0.36699	0.05176	0.8043	0.465314	4	0.024490

*parameters excluded from the model: $k_2 = 0$, $k_3 = 0$, $k_4 = D_{OF,\ maximum}$

Table 4. Pearson correlation matrix describing relationships between physical variables and biological observations (abbreviations in Table 1) of the May 1998 Bonsall Creek estuary survey. $N = 14$ (fullest data set with no missing observations). Note all taxa except CRUS (unidentified crustaceans sampled with the corer) are from epibenthic sled samples.

	DOF	*G*	AMPH	CRUS	CALN	HARP	COPE	CIRN	OSTR
DOF	1								
G	0.608382	1							
AMPH	0.349558	0.307816	1						
CRUS	-0.16965	0.145907	0.267807	1					
CALN	0.157047	0.561084	-0.09651	0.294023	1				
HARP	0.099365	0.105896	-0.16741	-0.39801	0.077307	1			
COPE	-0.02998	0.37159	-0.1671	-0.01862	0.839712	0.312839	1		
CIRN	-0.02167	0.288205	-0.21461	0.176615	0.912438	0.07453	0.894261	1	
OSTR	0.086651	0.018472	0.540458	-0.20262	-0.17319	0.112431	-0.19494	-0.20368	1

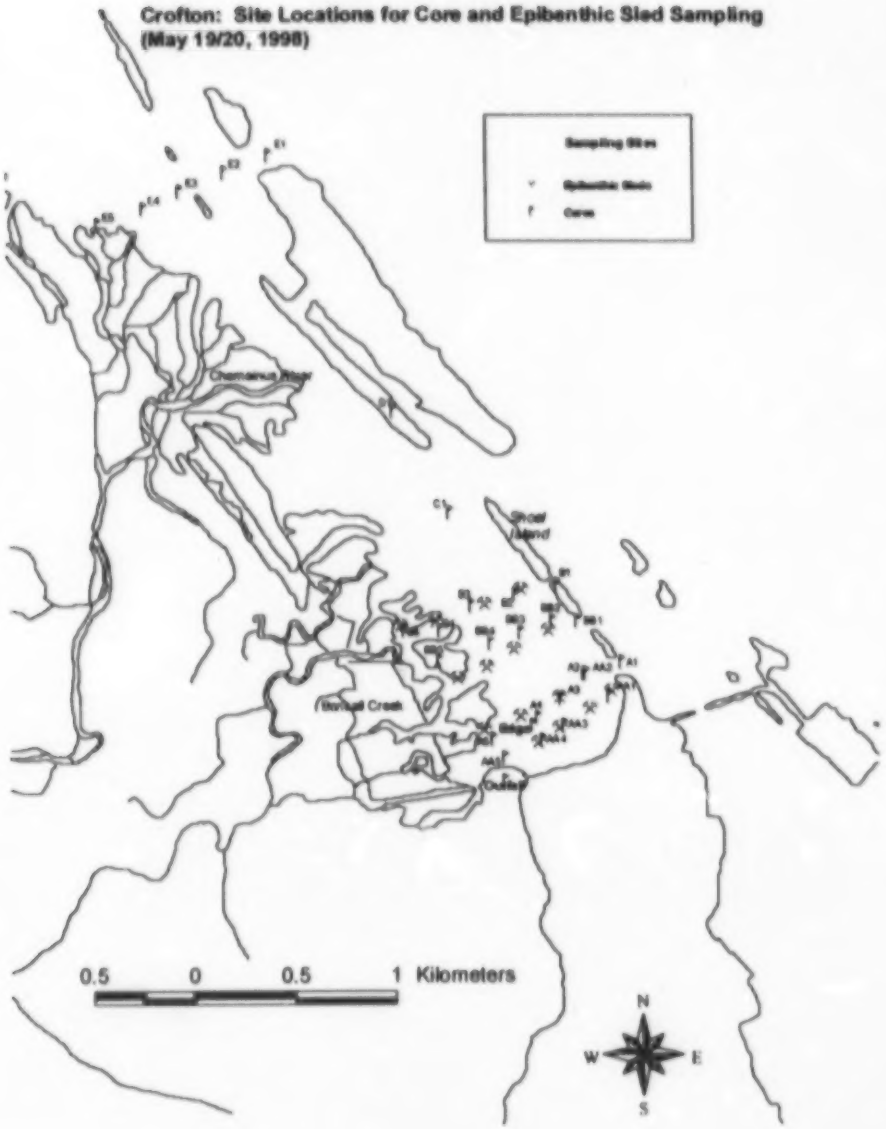
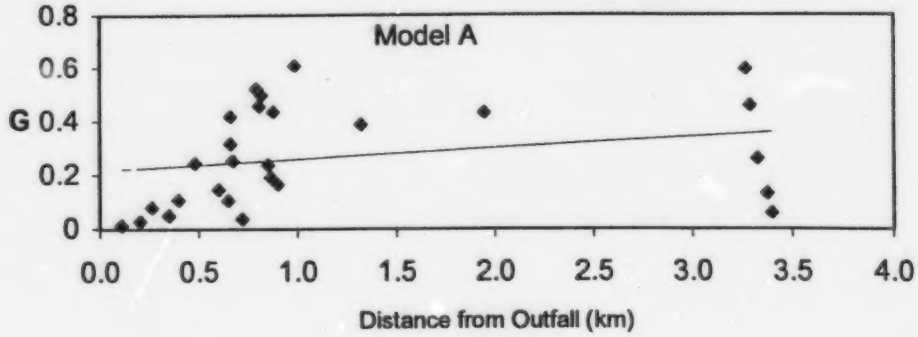
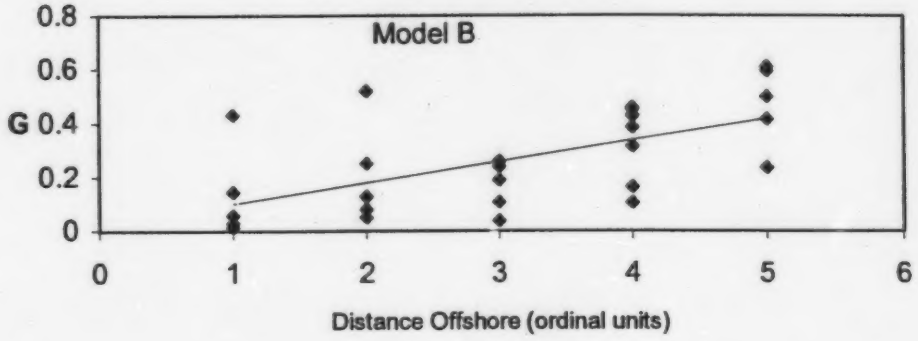


Fig. 1. Map of the Bonsall Creek estuary indicating the Crofton Pulp and Paper Mill settling pond outfall and sample sites of the May 1998 survey





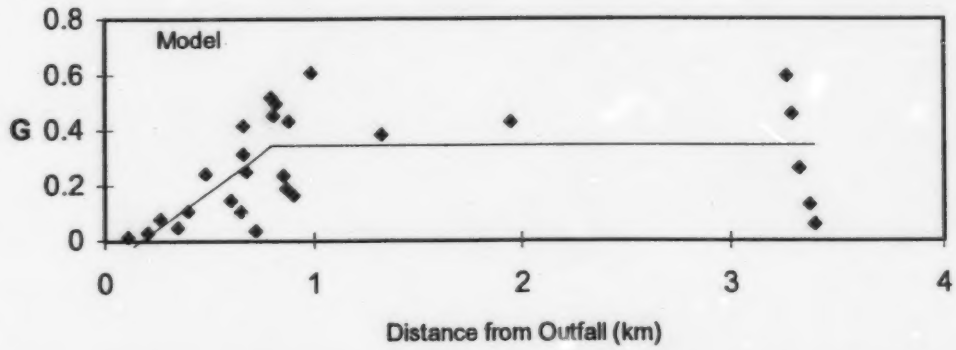


Fig. 2. Three models proposed to explain the distribution of sediment size composition (G) of core samples in the Bonsall Creek estuary. The lines indicate the least-square fit of each model and the points represent the observations. Model A) linear model assuming that the outfall has an effect on G over the full survey range, model B) linear model assuming that the offshore distance has a linear relationship with G, model C) rectilinear model assuming that the outfall has a linear effect on G up to a certain distance, beyond which it has no effect.

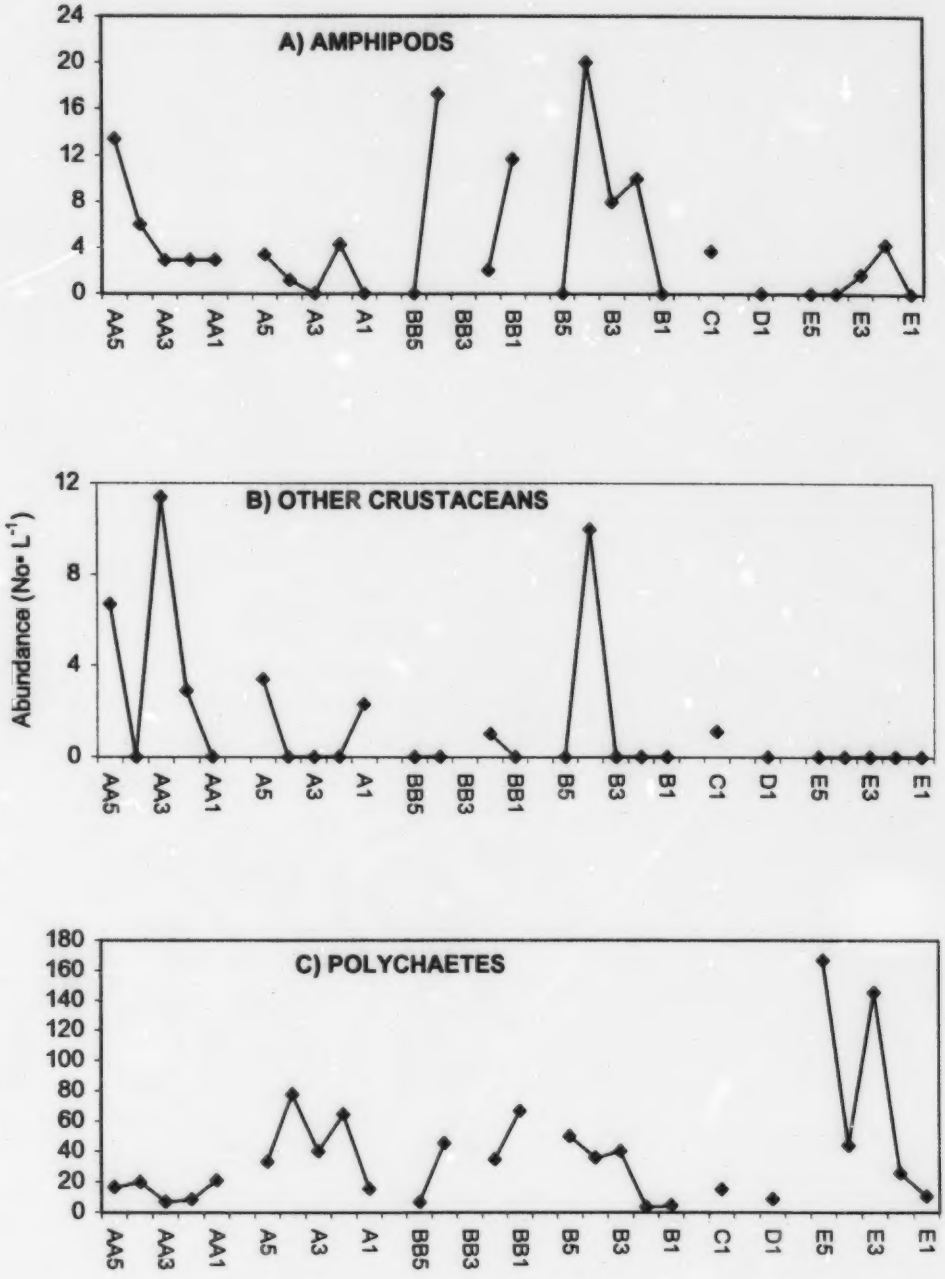


Fig. 3. Abundance of infauna from core samples (No.L^{-1}) collected at the Bonsall Creek estuary May 19-20 1998. Sample sites are grouped by transect, and arranged from closest (AA) to furthest (E) transect from the outfall. Note that this does not mean that the individual sample sites are arranged in proximity to the outfall (e.g. AA is closer than A, but A5 is closer than AA4).

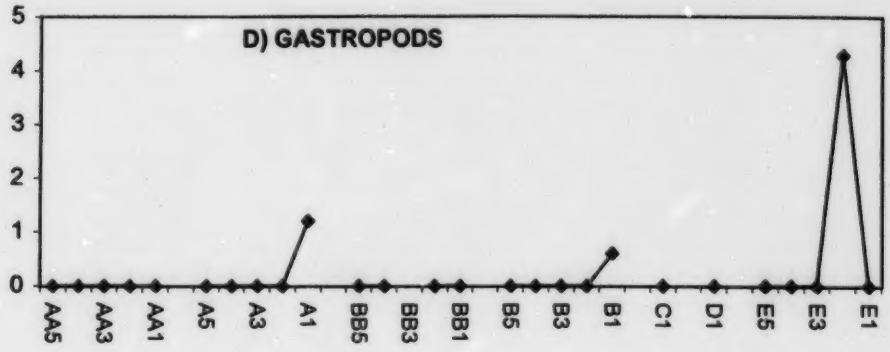


Fig. 3 Continued.

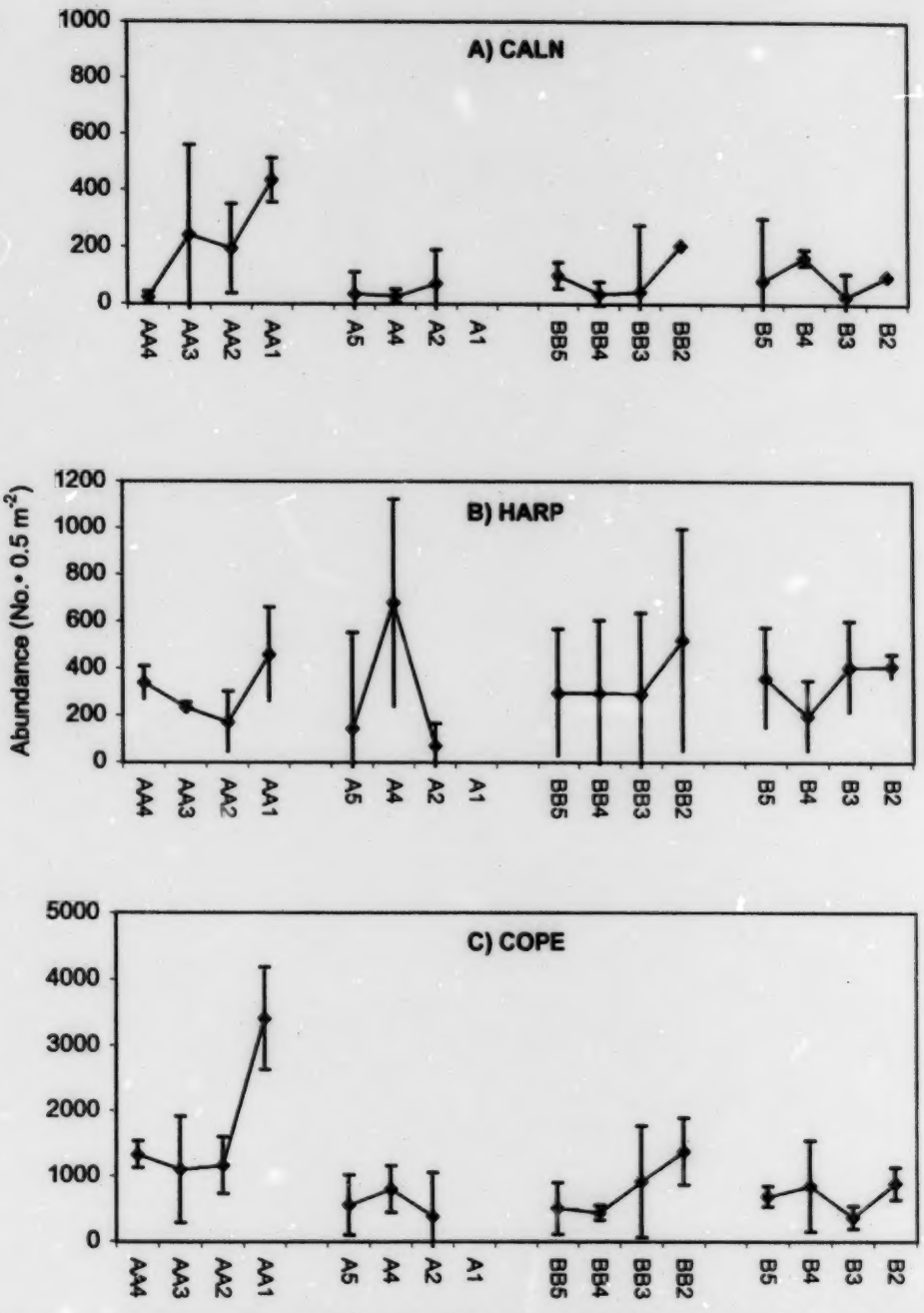
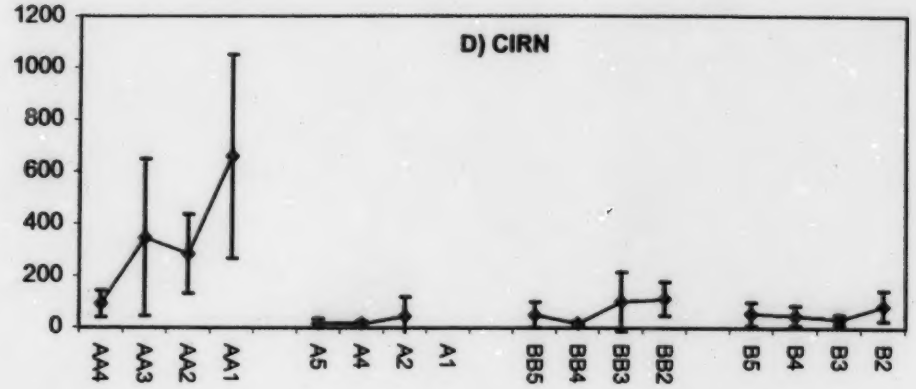
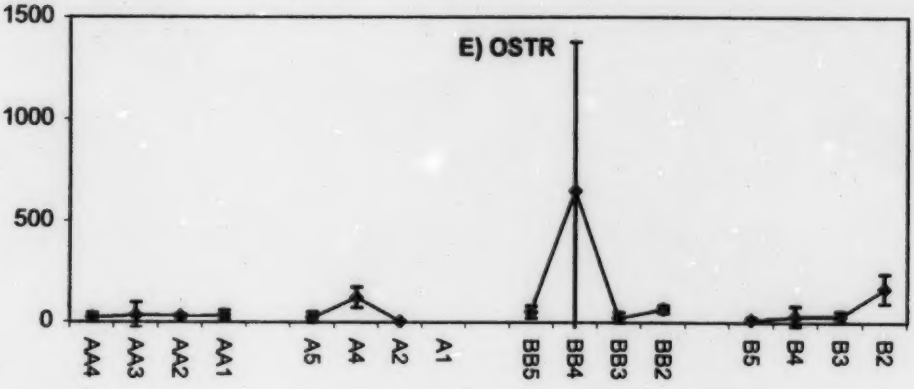
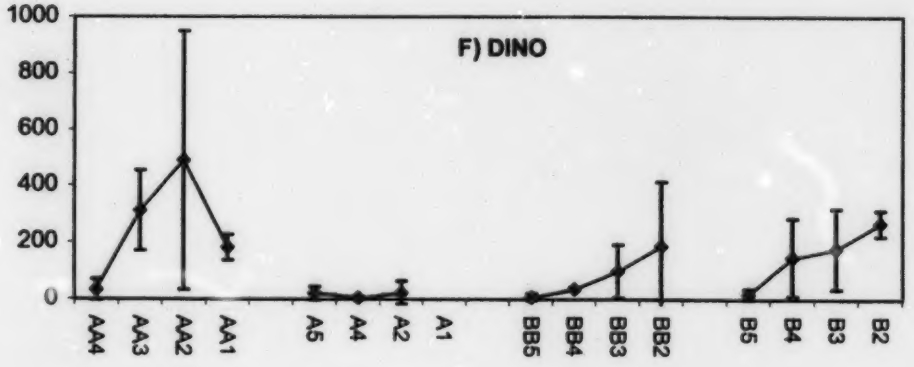


Fig. 4. Abundance of fauna (No. 0.5 m^{-2}) from the epibenthic sled samples collected at the Bonsall Creek estuary May 19-20 1998. Sample sites are grouped by transect, and arranged from closest (AA) to furthest (E) transect from the outfall. Note that this does not mean that the individual sample sites are arranged in proximity to the outfall (e.g. AA is closer than A, but A5 is closer than AA4). CI indicates 95%% confidence intervals. See Appendix C for codes.







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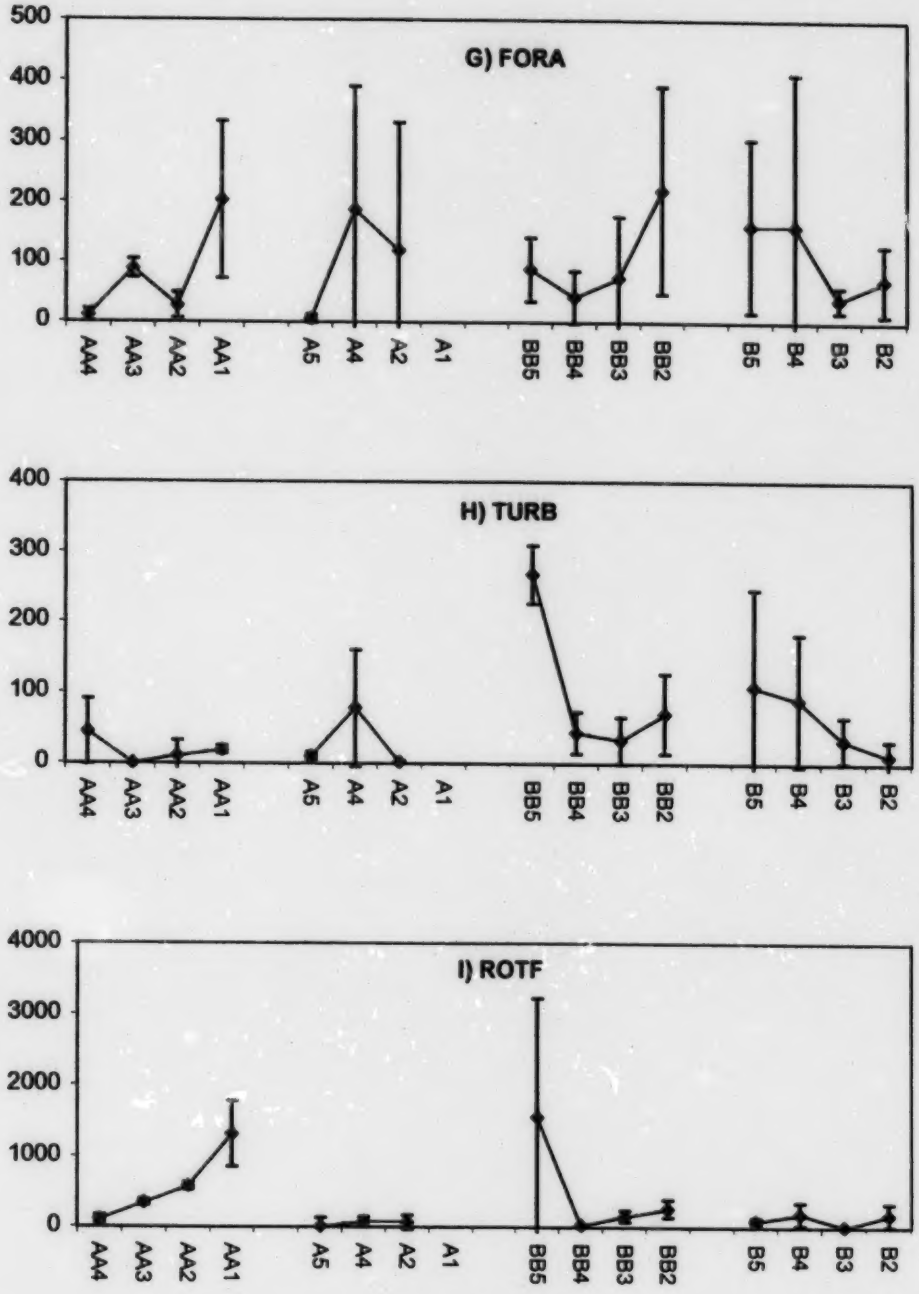

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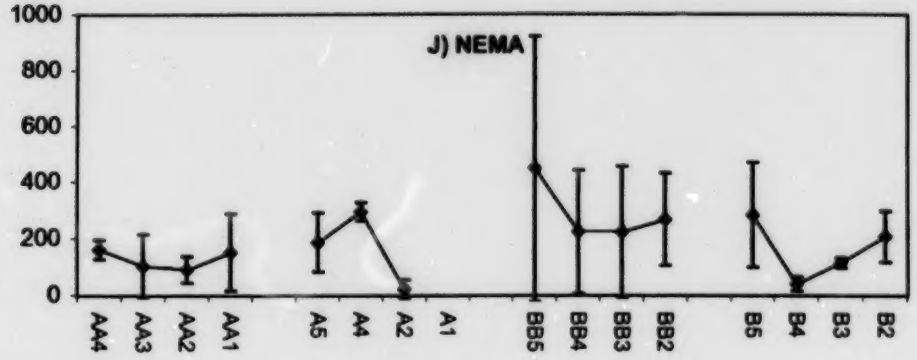
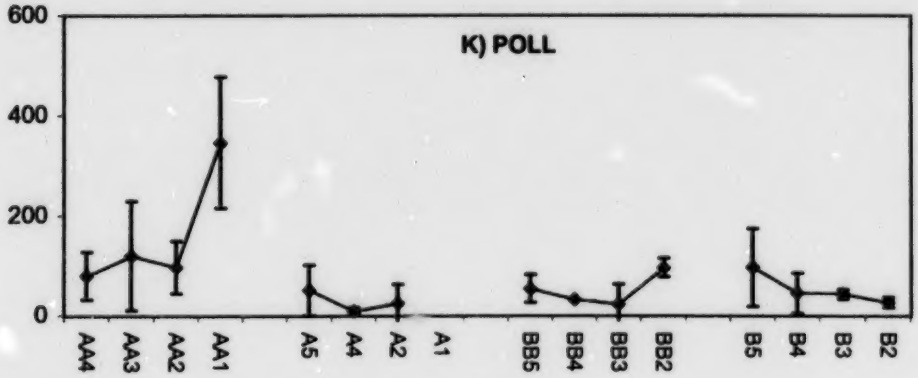




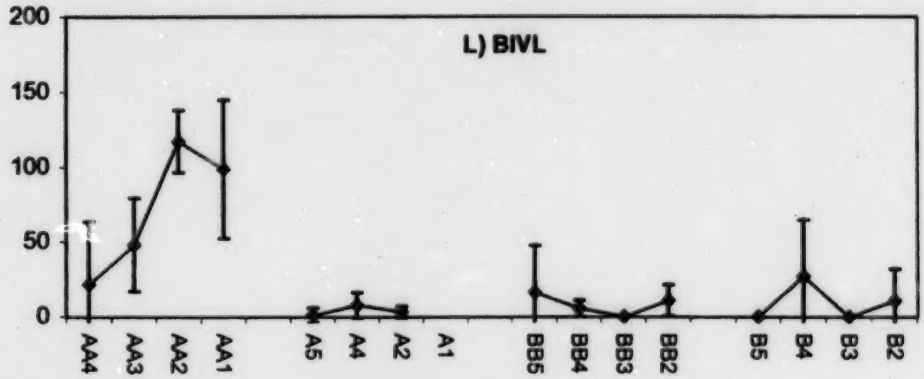
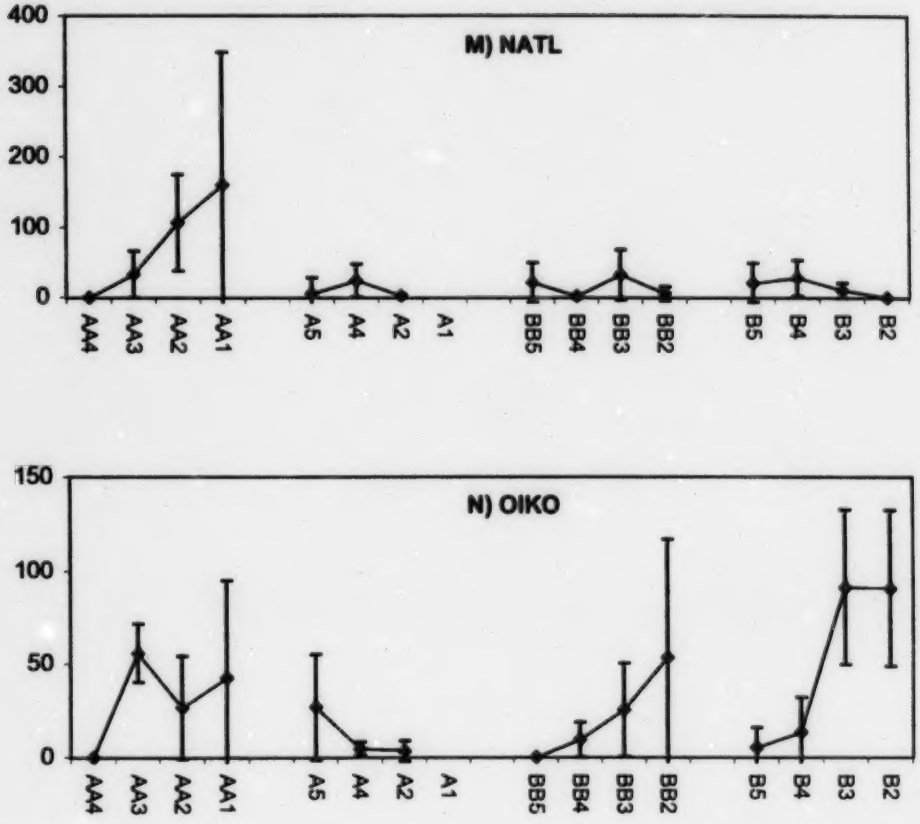


Fig. 4. (continued)



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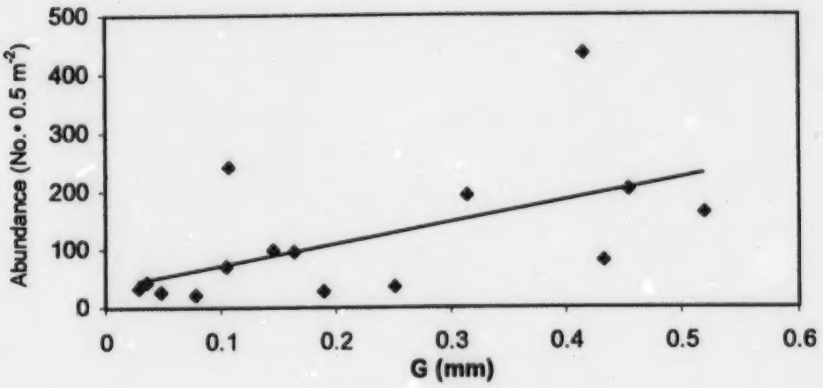

Fig. 5. The relationship between sediment size composition and calanoid copepod abundance in epibenthic sled samples from survey of the Bonsall Creek estuary.

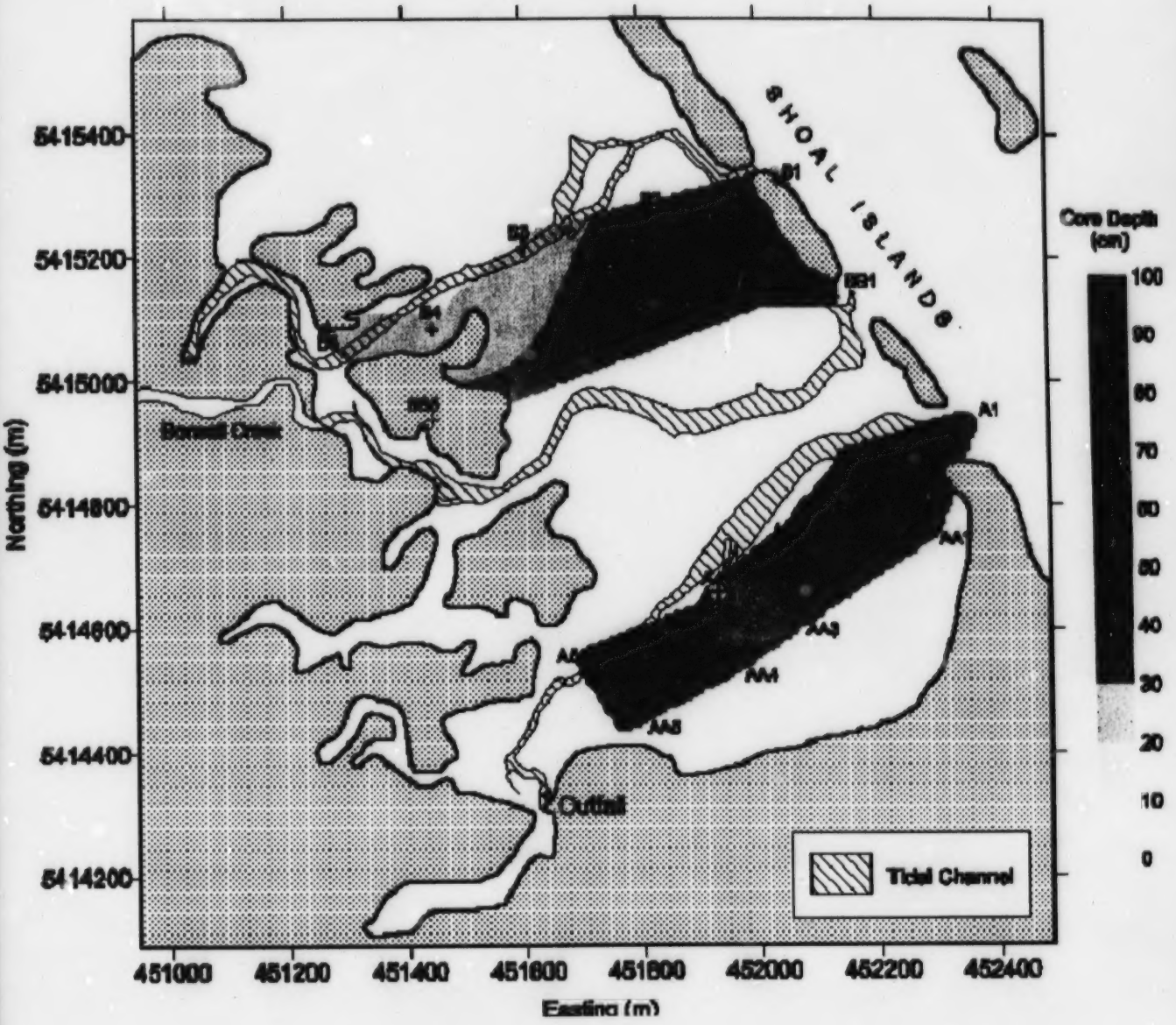

Fig. 6. Map of the Bonsall Creek estuary showing area of the mudflat affected by gel-mud, as indicated by the depth a core could be pushed into the sediment. Contour intervals –10cm.

LIST OF APPENDICES:

APPENDIX A. Tabulated data (no. 0.5 m^{-2}) for invertebrates from epibenthic sled sampling. See Appendix C for codes. * indicates vascular plant debris present in samples.

APPENDIX B. Abundance of invertebrates (no. dm^{-3}) from can cores.

APPENDIX C. Taxa of invertebrates obtained in epibenthic sled sampling and codes used in Appendix A and elsewhere in this report.

APPENDIX D. Sediment grain size data from the uppermost 10 cm of core samples and total length of core samples.

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APPENDIX F. Daily loadings of suspended solids (kg) from the Crofton pulp mill water filtration plant, 1998-1999. Data from Environment Canada provided to DFO in April 1999.

APPENDIX G. Method for computing area of upstream portion of tidal channel AA.

APPENDIX H. Methods used to estimate annual and daily sedimentation rates.

APPENDIX I. Abridged report from Precision Identification (1998) concerning Bonsall Creek estuary vegetation mapping.

APPENDIX A. Tabulated data (no. 0.5 m^{-2}) for invertebrates from epibenthic sled sampling. See Appendix C for codes. *indicates vascular plant debris present in samples.

	DINO	FORA	HYDR	CAMP	DIPH	CTEN	TURB	ROTF	NEMA	OLIG	SABL
A2-1	2	4	-	-	-	-	2	12	3	-	1
A2-2	-	17	-	-	-	-	-	10	10	1	1
A2-3	64	336	-	1	-	-	3	168	56	1	4
A4-1	1	368	-	-	-	-	88	1	304	2	-
A4-2	3	184	2	-	-	-	144	96	264	6	3
A4-3	8	8	-	-	-	-	-	112	320	-	-
A5-1	3	5	-	-	1	-	9	5	112	-	2
A5-2	52	-	-	1	-	3	4	11	216	1	-
A5-3	3	8	-	-	-	2	17	10	232	2	7
AA1-1	176	336	-	-	-	-	16	1296	288	-	-
AA1-2	144	128	-	-	-	-	24	1728	104	16	-
AA1-3	224	144	-	16	-	-	16	912	64	16	-
AA2-1	128	16	-	-	-	33	-	561	128	-	-
AA2-2	416	48	-	-	-	-	-	624	48	-	16
AA2-3	928	16	-	-	-	-	32	544	97	-	-
AA3-1	384	80	-	-	-	-	-	368	48	17	-
AA3-2	240	96	-	-	-	-	-	320	160	16	-
AA4-1	-	-	-	-	-	-	-	160	131	-	-
AA4-2	64	16	-	-	-	-	52	96	165	1	-
AA4-3	32	16	-	-	-	-	80	64	192	1	-
B2-1	224	32	-	-	-	16	-	32	288	16	-
B2-2	272	128	-	-	16	-	-	320	208	32	-
B2-3	304	48	-	-	-	-	32	160	128	16	32
B3-1	320	48	-	-	-	-	-	1	128	-	-
B3-2	112	48	-	-	-	-	48	-	98	-	-
B3-3	96	17	-	-	-	-	50	16	118	1	-
B4-1	8	12	-	-	-	4	12	20	56	-	8
B4-2	208	416	-	-	-	-	176	240	48	-	-
B4-3	224	48	-	-	-	-	80	288	16	-	-
B5-1	32	64	-	-	-	-	82	112	466	17	16
B5-2	-	304	-	-	-	-	241	48	240	-	16
B5-3	16	112	-	-	-	-	-	113	147	17	-
BB2-1	49	226	-	-	-	-	114	368	164	-	-
BB2-2	96	368	-	-	-	-	80	144	208	48	32
BB2-3	416	64	-	-	-	16	16	272	432	-	-
BB3-1	128	176	-	-	-	-	64	160	432	16	32
BB3-2	4	36	-	-	-	-	24	80	22	-	-
BB3-3	160	8	-	-	-	-	8	224	216	-	-
BB4-1	32	4	-	-	-	-	24	32	40	-	-
BB4-2	40	40	-	-	-	-	72	16	424	40	-
BB4-3	32	80	-	-	-	-	32	32	208	16	34
BB5-1	-	33	-	-	-	-	308	96	81	-	-
BB5-2	3	115	-	-	-	-	260	1521	365	7	16
BB5-3	18	114	-	-	-	-	235	3047	901	1	-

Appendix A (continued)

	SERP	POLL	POLA	BIVL	NATL	NATA	ATYI	NUDI	ACAR	ARAN	CALN
A2-1	-	5	-	1	3	-	-	-	-	-	10
A2-2	-	5	-	1	-	-	-	-	-	-	8
A2-3	-	64	-	7	4	-	-	-	-	-	192
A4-1	-	4	-	2	1	1	-	-	1	-	8
A4-2	-	7	-	5	40	-	-	-	1	-	48
A4-3	-	16	-	16	32	-	16	-	-	-	24
A5-1	-	23	-	1	-	6	-	1	68	-	15
A5-2	-	116	-	-	8	-	-	-	2	-	44
A5-3	-	15	-	2	9	-	-	-	10	-	41
AA1-1	-	480	-	64	64	-	-	-	-	-	496
AA1-2	-	288	-	88	64	-	-	-	-	-	360
AA1-3	-	272	-	144	352	-	-	-	-	-	448
AA2-1	-	97	-	96	80	-	-	-	34	-	98
AA2-2	-	144	-	128	176	-	-	-	-	-	352
AA2-3	-	51	17	128	64	-	-	-	-	-	128
AA3-1	-	176	-	64	50	16	-	-	19	-	403
AA3-2	-	64	-	32	16	-	-	-	-	-	80
AA4-1	-	112	-	-	-	-	-	-	263	-	32
AA4-2	-	96	-	64	-	-	-	-	190	-	32
AA4-3	-	32	-	-	-	-	-	-	278	-	-
B2-1	-	32	-	-	-	-	-	-	32	-	48
B2-2	-	16		32	-	-	-	-	96	-	64
B2-3	-	32	-	-	-	-	-	-	-	-	176
B3-1	-	48	-	-	16	-	-	-	81	-	48
B3-2	-	33	-	-	16	-	-	-	4	-	-
B3-3	-	48	-	-	-	-	-	-	369	1	33
B4-1	-	8	-	-	4	-	-	-	4	-	24
B4-2	-	80	-	16	32	-	-	-	112	-	80
B4-3	-	48	-	64	48	-	-	-	-	-	384
B5-1	-	17	-	-	48	-	-	-	92	-	16
B5-2	-	128	-	-	-	-	-	-	355	-	144
B5-3	32	145	-	-	16	-	-	-	364	-	80
BB2-1	1	96	-	-	-	-	-	-	97	1	33
BB2-2	-	80	-	16	-	-	-	-	64	-	144
BB2-3	-	113	-	16	16	-	-	-	-	-	432
BB3-1	-	-	-	-	64	-	-	-	32	-	80
BB3-2	-	4	-	-	-	-	-	-	155	-	8
BB3-3	-	64	-	-	32	-	-	-	44	-	41
BB4-1	-	32	-	8	4	-	-	-	8	-	24
BB4-2	-	32	-	8	-	-	-	-	16	-	-
BB4-3	-	32	-	-	-	-	-	-	2	-	80
BB5-1	-	33	-	48	48	-	-	-	965	15	196
BB5-2	-	48	-	-	-	-	-	1	827	33	33
BB5-3	-	81	-	-	16	-	-	1	1231	66	66

Appendix A (continued)

	CYCL	HARP	COPE	CIRN	CIRC	PODO	OSTR	CUMA	TANA	CALL	AMPI
A2-1	-	24	37	7	-	-	1	-	-	-	-
A2-2	-	23	46	4	-	-	-	-	-	-	-
A2-3	-	168	1064	120	-	-	6	7	-	1	-
A4-1	-	304	440	10	-	-	128	3	-	-	-
A4-2	-	648	992	13	-	-	160	5	-	-	1
A4-3	24	1088	976	24	8	-	72	-	-	-	-
A5-1	-	169	560	4	7	-	4	1	-	-	-
A5-2	-	172	1000	28	1	2	20	-	-	-	-
A5-3	-	88	120	15	1	-	42	2	-	-	-
AA1-1	-	545	4180	1026	-	-	16	-	-	-	-
AA1-2	8	576	3160	616	-	8	56	16	-	-	-
AA1-3	-	256	2880	336	32	-	32	16	16	-	-
AA2-1	-	115	741	146	-	-	32	-	-	-	-
AA2-2	-	96	1488	416	-	-	32	-	-	-	-
AA2-3	-	305	1265	289	-	-	16	-	-	-	-
AA3-1	-	246	1520	500	-	16	1	-	-	-	-
AA3-2	-	224	688	192	-	-	64	-	-	-	-
AA4-1	-	339	1250	67	-	-	32	-	1	-	-
AA4-2	-	276	1219	144	-	-	32	-	-	-	-
AA4-3	-	403	1542	64	-	-	-	16	-	-	-
B2-1	-	384	736	48	16	-	96	-	-	-	-
B2-2	-	464	784	64	-	-	176	-	-	-	-
B2-3	-	384	1136	144	-	-	224	-	-	-	-
B3-1	-	544	448	48	-	-	48	-	-	-	-
B3-2	-	213	192	16	-	-	-	-	-	-	-
B3-3	-	463	468	33	-	-	32	-	-	-	-
B4-1	-	68	148	12	4	-	8	4	-	-	-
B4-2	-	336	1088	48	-	-	80	-	-	-	-
B4-3	16	192	1298	80	16	-	-	-	-	-	-
B5-1	1	149	770	16	-	-	17	-	-	-	-
B5-2	-	514	529	96	16	-	-	-	-	-	-
B5-3	-	417	770	50	-	-	16	-	-	-	-
BB2-1	-	988	1189	64	-	16	65	16	-	-	-
BB2-2	-	400	1040	96	-	-	80	16	-	-	-
BB2-3	-	176	1891	176	-	-	48	-	-	-	-
BB3-1	-	624	1648	96	-	16	16	-	-	-	-
BB3-2	-	28	141	-	-	-	4	-	-	-	-
BB3-3	-	217	965	203	-	-	48	1	-	-	-
BB4-1	-	104	348	8	-	-	48	-	-	-	-
BB4-2	24	608	544	24	-	-	1328	-	16	-	-
BB4-3	-	176	416	16	-	-	576	-	-	-	-
BB5-1	51	522	874	99	-	-	65	-	-	-	-
BB5-2	-	323	449	16	-	-	65	-	-	-	-
BB5-3	-	44	182	32	-	-	19	1	-	-	-

Appendix A (continued)

	PLEU	ANIS	CORO	SPHR	MYSD	CRAZ	PAGU	BRCH	ENTO	HYPO	CERA
A2-1	-	-	-	-	-	-	-	-	-	-	-
A2-2	-	-	1	-	-	-	-	-	-	-	-
A2-3	-	-	1	1	-	-	-	-	-	-	-
A4-1	-	-	3	-	-	-	-	-	-	-	-
A4-2	-	-	3	-	-	-	-	-	-	-	-
A4-3	-	-	-	-	-	-	-	-	-	-	-
A5-1	-	-	-	-	-	1	-	-	-	-	-
A5-2	1	-	-	-	-	2	-	-	-	-	-
A5-3	-	-	-	-	-	-	-	-	-	-	-
AA1-1	-	-	-	-	-	-	-	-	-	-	-
AA1-2	-	-	-	-	-	-	-	-	-	-	-
AA1-3	-	-	-	-	-	-	-	16	-	-	-
AA2-1	-	-	-	-	1	33	-	-	-	-	-
AA2-2	-	-	-	-	-	64	-	-	-	-	-
AA2-3	-	-	16	-	-	16	-	-	-	-	-
AA3-1	-	-	-	-	-	1	-	-	-	-	-
AA3-2	-	-	-	-	-	-	-	-	-	-	-
AA4-1	-	-	-	-	-	-	-	-	-	-	-
AA4-2	-	-	-	-	-	-	-	-	-	-	-
AA4-3	-	-	-	-	-	-	-	-	-	-	-
B2-1	-	-	-	-	-	-	-	-	-	-	-
B2-2	-	-	-	-	-	-	-	-	-	-	-
B2-3	-	-	-	-	-	16	-	-	-	-	-
B3-1	-	-	-	-	-	-	-	-	-	-	-
B3-2	-	-	-	-	-	-	-	-	-	-	-
B3-3	-	-	-	16	-	16	-	-	-	-	16
B4-1	-	-	-	-	-	-	-	-	-	-	-
B4-2	-	-	-	-	-	-	-	-	-	-	-
B4-3	-	-	-	-	-	-	-	-	-	-	-
B5-1	-	-	-	-	-	16	-	-	16	-	-
B5-2	-	-	20	-	-	16	-	-	-	-	-
B5-3	-	-	1	-	-	-	-	-	-	-	-
BB2-1	-	-	-	-	-	-	-	-	-	-	-
BB2-2	-	16	-	-	-	16	-	-	-	-	-
BB2-3	-	-	-	-	1	-	-	16	-	-	-
BB3-1	-	-	16	-	-	1	-	-	-	-	-
BB3-2	-	-	4	-	-	-	-	-	-	-	-
BB3-3	-	-	-	-	8	8	-	-	-	-	-
BB4-1	-	-	-	-	-	-	-	-	-	-	-
BB4-2	-	-	-	-	-	8	-	-	-	-	-
BB4-3	-	-	-	-	-	-	-	-	16	-	-
BB5-1	-	1	-	-	-	-	1	-	-	-	-
BB5-2	-	-	-	-	-	-	-	-	-	-	-
BB5-3	-	-	-	1	-	-	-	-	-	1	-

Appendix A (continued)

	CHIL	CHIP	CHIA	EPHL	SALN	FRIL	OIKO	TLST	TROC	EGG	EGGM
A2-1	-	-	-	-	-	-	1	-	-	12	3
A2-2	-	-	-	-	-	-	-	-	1	23	-
A2-3	-	-	-	-	-	-	9	-	2	480	1
A4-1	-	-	-	-	-	-	2	-	-	192	-
A4-2	-	-	-	-	-	-	4	-	1	288	6
A4-3	-	-	-	-	-	-	8	-	-	272	16
A5-1	-	-	-	-	-	-	12	-	4	688	1
A5-2	2	-	-	-	-	-	56	-	100	220	-
A5-3	2	-	-	-	-	-	13	1	9	142	2
AA1-1	-	-	-	-	-	-	16	-	-	3584	-
AA1-2	-	-	8	-	-	-	96	-	-	3016	16
AA1-3	-	-	-	-	-	-	16	-	16	1568	16
AA2-1	-	-	-	-	-	33	-	-	16	857	1
AA2-2	-	-	-	-	-	-	32	-	-	1456	-
AA2-3	-	-	-	-	-	33	48	-	48	2402	-
AA3-1	-	-	-	-	-	16	64	-	16	2545	-
AA3-2	-	-	-	-	-	-	48	-	-	2192	-
AA4-1	-	-	-	-	-	-	-	-	-	129	16
AA4-2	1	-	-	-	-	-	-	-	-	371	16
AA4-3	-	-	-	-	-	-	-	-	-	850	-
B2-1	48	-	-	16	-	-	112	-	-	8224	-
B2-2	-	-	-	-	-	16	48	-	-	2544	16
B2-3	-	-	-	-	-	-	112	-	-	4672	16
B3-1	32	-	-	-	-	-	49	-	-	2628	16
B3-2	-	-	-	-	-	-	113	-	-	2035	1
B3-3	-	-	-	-	1	-	112	-	16	1515	16
B4-1	-	-	-	-	4	-	8	4	4	1868	-
B4-2	-	-	-	-	-	-	-	-	-	4112	48
B4-3	-	-	-	-	-	-	32	16	-	2918	-
B5-1	16	-	-	-	1	-	-	1	16	618	48
B5-2	16	-	-	-	-	-	16	-	32	224	32
B5-3	32	-	-	-	-	-	-	-	-	369	-
BB2-1	17	-	-	-	-	-	-	-	-	737	65
BB2-2	16	-	-	-	-	-	112	-	96	1824	80
BB2-3	16	-	-	-	-	32	48	-	96	3874	16
BB3-1	16	-	-	-	-	-	48	-	48	1264	48
BB3-2	25	-	-	-	-	-	4	-	4	124	12
BB3-3	34	8	-	-	-	-	24	-	-	856	9
BB4-1	4	-	-	-	-	-	12	-	8	1020	4
BB4-2	-	-	-	-	-	16	-	-	24	1680	-
BB4-3	-	-	-	-	-	16	16	-	48	1044	-
BB5-1	16	-	-	-	-	-	-	-	-	160	-
BB5-2	-	-	-	-	-	-	-	-	16	193	-
BB5-3	-	-	-	-	1	-	-	1	18	265	-

APPENDIX B. Abundance of invertebrates (no. dm^{-3}) from can cores.

Site	Volume (dm^3)	Polychaetes	Amphipods	Other Crustaceans	Gastropods	Bivalves	Misc. Taxa
A1	1.8	15.6	-	2.2	1.1	3.3	2.8
A2	0.7	64.3	4.3	-	-	-	1.4
A3	0.5	40.0	-	-	-	2.0	2.0
A4	0.9	77.8	1.1	-	-	-	1.1
A5	0.6	33.4	-	3.3	-	-	-
AA1	0.7	21.4	2.9	-	-	-	-
AA2	0.7	8.6	2.9	2.9	-	-	7.1
AA3	0.7	7.1	2.9	11.4	-	-	-
AA4	1.0	20.0	6.0	-	-	-	-
AA5	0.3	16.7	13.3	6.7	-	-	-
B1	1.6	4.4	-	-	0.6	8.8	-
B2	0.6	3.3	10.0	-	-	-	-
B3	1.0	40.0	8.0	-	-	-	6.0
B4	0.5	36.0	20.0	10.0	-	-	10.0
B5	0.7	50.0	-	-	-	-	-
BB1	0.6	66.7	11.7	-	-	-	1.7
BB2	1.0	35.0	2.0	1.0	-	4.0	2.0
BB4	1.1	45.5	17.3	-	-	-	0.9
BB5	0.9	6.7	-	-	-	-	-
C1	1.9	15.3	3.7	1.1	-	3.2	0.5
D1	1.4	8.6	-	-	-	0.7	1.4
E1	1.7	10.6	-	-	-	5.9	-
E2	0.7	25.7	4.3	-	4.3	2.9	-
E3	0.6	145.0	1.7	-	-	5.0	-
E4	0.8	43.8	-	-	-	-	-
E5	0.9	166.7	-	-	-	-	-

APPENDIX C. Taxa of invertebrates obtained in epibenthic sled sampling and codes used in Appendix A and elsewhere in this report.

Code	Order/Family	Stage	Group
ACAR	Acari	adult	ARACHNIDA
AMPI	Ampithoidae	adult	AMPHIPODA
ANIS	Anisogammaridae	adult	AMPHIPODA
ARAN	Araneae	adult	ARANEAE
ATYI	Atyidae	adult	GASTROPODA
BIVL	Bivalvia	larvae	BIVALVIA
BIVL	Bivalvia	adult	BIVALVIA
BRCH	Brachyura	zoea	BRACHYURA
CALL	Calliopiidae	adult	AMPHIPODA
CALN	Calanoida	adult	COPEPODA
CAMP	Campanulariidae	medusae	HYDROIDA
CERA	Ceratopogonidae	larvae	DIPTERA
CHIA	Chironomidae	larvae	DIPTERA
CHIL	Chironomidae	pupae	DIPTERA
CHIP	Chironomidae	adult	DIPTERA
CIRC	Cirripedia	nauplii	CIRRIPEDIA
CIRN	Cirripedia	cypris	CIRRIPEDIA
COPE	Copepoda	nauplii	COPEPODA
CORO	Corophiidae	adult	AMPHIPODA
CRAZ	Crangonidae	zoea	DECAPODA
CUMA	Cumacea	adult	CUMACEA
CYCL	Cyclopoida	adult	COPEPODA
DINO	Dinoflagellida		DINOFLAGELLIDA
DIPH	Calycophorae		SIPHONOPHORA
EGG			EGG
EGGM			EGG MASS
ENTO	Entomobryidae	adult	COLLEMBOLA
EPHL	Ephydridae	larvae	DIPTERA
FORA	Foraminifera		FORAMINIFERA
FRIL	Frillariidae	adult	LARVACEA
HARP	Harpacticoida	adult	COPEPODA
HYDR	Hydroida	sessile	HYDROIDA
HYPO	Hypogastruridae	adult	COLLEMBOLA
MYSD	Mysidae	adult	MYSIDACEA
NATA	Naticidae	larvae	GASTROPODA
NATL	Naticidae	adult	GASTROPODA
NEMA	Nematoda	adult	NEMATODA
NUDI	Nudibranchia	adult	GASTROPODA
OIKO	Oikopleuridae	adult	LARVACEA

Appendix C (continued)

Code	Order/Family	Stage	Group
OLIG	Oligochaeta	adult	OLIGOCHAETA
OSTR	Ostracoda	adult	OSTRACODA
PAGU	Paguridae	adult	ANOMURA
OSTR	Ostracoda	adult	OSTRACODA
PAGU	Paguridae	adult	ANOMURA
POLA	Polychaeta	larvae	POLYCHAETA
POLL	Polychaeta	adult	POLYCHAETA
ROTF	Rotifera	adult	ROTIFERA
SABL	Sabellidae	adult	POLYCHAETA
SALN	Saldidae	adult	HEMIPTERA
SERP	Serpulidae	adult	POLYCHAETA
SPHR	Sphaeromatidae	adult	ISOPODA
TANA	Tanaidae	adult	TANAIDACEA
TLST	Teleost	larvae	TELEOST
TROC	Trochophore		TROCHOPHORE
TURB	Turbellaria	adult	PLATYHELMINTHES

APPENDIX D. Sediment grain size data from the uppermost 10 cm of core samples and total length of core samples.

	Particle Size Distribution					Percent by Weight, by Category					
	Percent Less Than by Weight (mm)					% Gravel	% Sand	% Silt	% Clay		
	Dry Sieve	Wet Sieve		Pipette		>2.00	<2.00	<0.053	<0.002	Textural	Core Length
	2.00	0.250	0.125	0.053	0.002	mm	>0.053	>0.002	mm	Category	cm
A1	98.05	43.59	22.40	14.64	3.89	1.95	85.07	10.97	3.96	Loamy sand	40
A2	96.75	79.85	69.98	49.81	10.72	3.25	48.51	40.41	11.08	Loam	40
A3	99.71	68.46	54.86	31.66	7.34	0.29	68.25	24.39	7.36	Sandy loam	58
A4	100.00	84.57	79.22	67.46	17.08	0.00	32.54	50.38	17.08	Loam	28
A5	99.62	93.02	89.09	78.87	20.00	0.38	20.82	59.10	20.08	Silt loam	58
AA1	100.00	57.07	39.63	19.74	4.10	0.00	80.26	15.64	4.10	Loamy sand	50
AA2	99.72	70.51	54.41	26.20	5.39	0.28	73.73	20.87	5.40	Sandy loam	60
AA3	99.66	92.11	83.38	51.68	9.93	0.34	48.14	41.89	9.97	Loam	40
AA4	99.69	93.38	84.80	60.66	9.51	0.31	39.15	51.30	9.54	Silt loam	43
AA5	100.00	99.63	98.50	95.65	26.24	0.00	4.35	69.40	26.24	Silt loam	46[1]
B1	76.43	18.38	10.81	7.92	2.23	23.57	89.64	7.45	2.91	Sand	30
B2	91.34	64.66	53.79	38.25	7.28	8.66	58.12	33.91	7.97	Sandy loam	36
B3	94.14	66.93	52.54	35.67	7.54	5.86	62.11	29.89	8.01	Sandy loam	20
B4	56.90	16.61	11.66	8.21	1.80	43.10	85.57	11.26	3.17	Loamy sand	20
B5	63.80	39.73	23.33	12.13	2.34	36.20	80.99	15.35	3.68	Loamy sand	30
BB1	99.17	87.61	74.46	33.38	5.87	0.83	66.34	27.74	5.92	Sandy loam	41
BB2	99.62	57.51	41.70	18.04	3.18	0.38	81.90	14.92	3.19	Loamy sand	31
BB3	99.79	92.32	86.33	74.57	18.21	0.21	25.27	56.48	18.24	Silt loam	61
BB4	95.24	68.22	48.94	30.05	6.07	4.76	68.45	25.18	6.37	Sandy loam	37
BB5	98.25	80.47	65.76	44.33	7.91	1.75	54.88	37.08	8.05	Sandy loam	36
C1	99.87	75.35	59.03	22.22	3.70	0.13	77.75	18.54	3.71	Loamy sand	30
D1	100.00	91.69	39.80	18.96	4.06	0.00	81.04	14.91	4.06	Loamy sand	59
E1	99.61	59.94	23.70	11.37	2.43	0.39	88.59	8.98	2.43	Sand	36
E2	84.81	43.42	26.98	15.05	2.92	15.19	82.26	14.30	3.45	Loamy sand	42
E3	99.31	80.54	59.48	31.82	4.75	0.69	67.96	27.26	4.78	Sandy loam	39
E4	99.84	98.45	90.97	48.17	8.26	0.16	51.76	39.97	8.27	Loam	31
E5	100.00	99.68	93.32	67.93	10.95	0.00	32.07	56.98	10.95	Silt loam	35

[1]Core was able to be pushed to 100 cm but personnel could not retrieve full length because of consistency of the sediment.

Appendix E. Indices of substrate size composition from core samples.

The visible effect of the settling pond flushing on the Bonsall Creek estuary is the accumulation of a fine sediment or gel mud. The following indices were compared to see which would be the most useful for describing the sediments:

1) *%F* = the percentage of sand, silt and clay passing through a 2 mm sieve

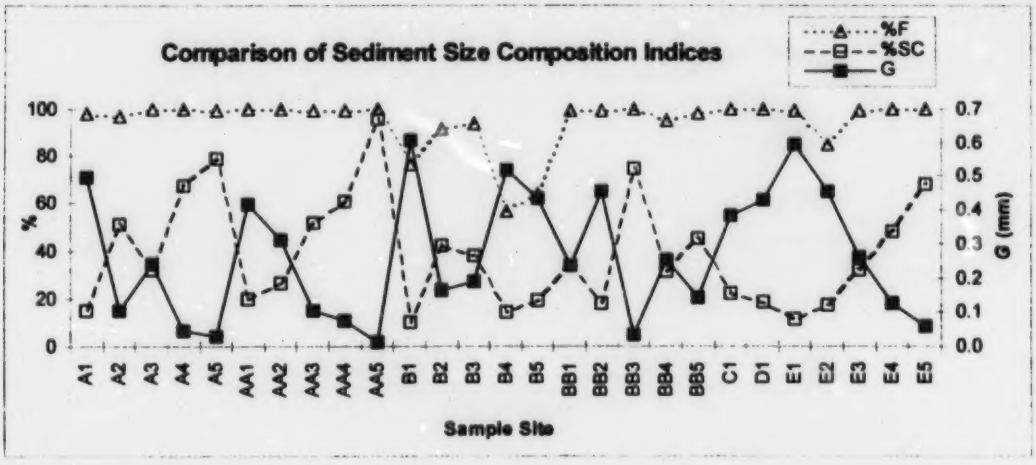
2) *%SC* = the percentage of silt and clay in the fines
= (%Silt+%Clay) / %F

3) *G* = Geometric Mean Particle Size of fines:

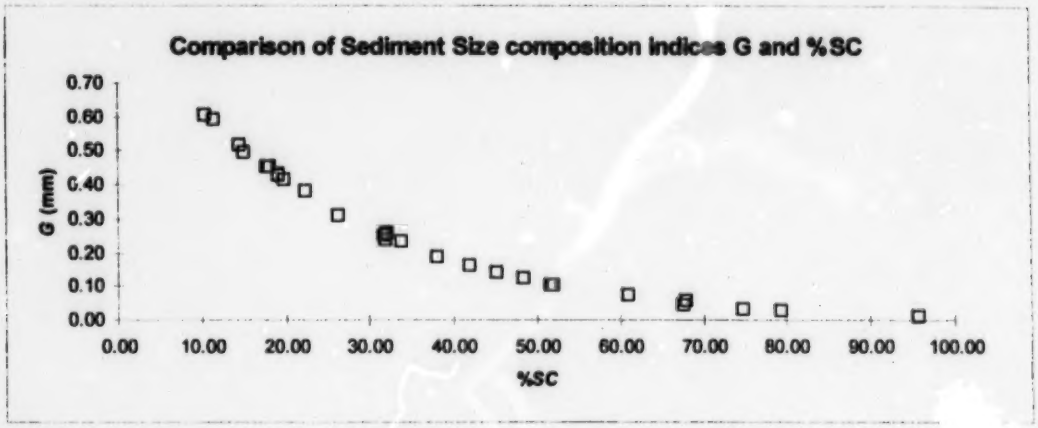
$$\sum_{w_i} \sqrt{\prod s_i^{w_i}}$$

where: w_i = the mass of sediment in size class *i*
s_i = size class *i* midpoint.

Plots of the three indices by station indicate that *%SC* and *G* and measuring similar things in the substrate (though they are negatively correlated), while *%F* is measuring something different:



Since the estuary region is a sandy mudflat in the absence of the settling pond sediment, it is likely that %*SC* is probably the best indicator of silt and clay accumulation. However, %*SC* and *G* are closely related (though not in a linear fashion):



G was adopted for further analyses because it is a more common sediment index.

Parameters and goodness of fit criteria for different models describing the sediment size composition (*G*) as a function of the distance from the Crofton Mill settling pond outfall (D_{OF}) and distance offshore (D_{OS}) along the transect axis. Least-squares fitting based on the observations of Table 1, limited only to transects AA and A ($N = 10$).

$$G' = \begin{cases} k_1 + k_2(D_{OF}) + k_3(D_{OS}); D_{OF} < k_4 \\ k_1 + k_2(k_4) + k_3(D_{OS}); D_{OF} \geq k_4, \end{cases}$$

Model	Parameters				Sums of Squares	Number of estimated parameters	Goodness of fit
	k_1	k_2	k_3	k_4	SSQ	P	SSQ/(N-2P)
A	-0.1082	0.6385	*	*	0.068819	2	0.011470
B	-0.1207	*	0.1017	*	0.060352	2	0.010059
C	-0.1082	0.6385	*	0.8785**	0.068819	3	0.017205
D	-0.1212	0.1105	0.0850	*	0.059989	3	0.014997
E	-0.0391	-0.5127	0.1310	0.3961	0.052194	4	0.026097

*parameters excluded from the model: $k_2 = 0$, $k_3 = 0$, $k_4 = D_{OF,\ maximum}$

** optimized $k_4 > D_{OF,\ maximum}$, so model A and C are identical.

APPENDIX F. Daily loadings of suspended solids (kg) from the Crofton pulp mill water filtration plant, 1998-1999. Data from B.C. Ministry of Environment, Lands, Parks, via DFO Habitat and Enhancement Branch in April 1999.

Date	TSS ($kg\ d^{-1}$)	Date	TSS ($kg\ d^{-1}$)
29-Mar-99	371	13-Jul-98	2.8
22-Mar-99	35.2	06-Jul-98	0
15-Mar-99	163.4	29-Jun-98	2.7
09-Mar-99	129.61	22-Jun-98	1.1
02-Mar-99	237.8	18-Jun-98	1.4
22-Feb-99	207.7	09-Jun-98	1.8
15-Feb-99	279	01-Jun-98	4.8
08-Feb-99	339.69	25-May-98	22
01-Feb-99	387.6	19-May-98	7.2
25-Jan-99	197.2	11-May-98	4.2
18-Jan-99	562.4	02-May-98	20
11-Jan-99	64.4		
04-Jan-99	125		
28-Dec-98	321.2		
14-Dec-98	304.8		
07-Dec-98	412.78		
30-Nov-98	431.2		
23-Nov-98	749.8		
16-Nov-98	192.4		
09-Nov-98	12		
02-Nov-98	12.5		
25-Oct-98	6.4		
19-Oct-98	16.1		
13-Oct-98	42		
06-Oct-98	1.9		
28-Sep-98	9.6		
21-Sep-98	11		
15-Sep-98	3.8		
08-Sep-98	42.9		
31-Aug-98	7.8		
25-Aug-98	0		
17-Aug-98	0		
10-Aug-98	2.1		
04-Aug-98	0		
27-Jul-98	18.7		
20-Jul-98	0		

APPENDIX G. Method for computing area of upstream portion of tidal channel AA.

The vegetation map developed by Campbell et al. (1982) from field work in June 1981 was compared with contemporary habitat mapping data based on interpretation of 1:6000 aerial photos obtained in June 1998 (Appendix I). An overlay of the general configuration of tidal channel AA in 1981 and 1988 showed little difference in the position of the shoreline. The 1981 map was digitized courtesy of Brad Mason, Habitat and Enhancement Branch, and imported into a GIS system (Arcview 3.1). Based on sediment characteristics (see above), it was assumed that the area of influence of the settling basin mud reached approximately 800 m seaward from the outfall. This distance was used when computing the area of the affected habitat in the channel, by GIS analysis of the tidal channel polygon.

APPENDIX H. Methods used to estimate annual and daily sedimentation rates.

The annual TSS discharge (kg yr^{-1}) was converted to a sediment flux (kg m^{-2} yr^{-1}) by standardizing the TSS discharge value by the depositional area of the tidal channel (20,160 m^{-2}). The sediment flux represents the amount of sediment discharged that would be distributed over the designated depositional area of the tidal channel (immediate 0.8 km) per year. Using a typical bulk density value (kg m^{-3}) of settled sediment, the sediment flux was then converted to a sedimentation rate (cm yr^{-1}). Bulk density represents the consolidation or packing extent of sediment grains within a certain volume of seabed. Thus, sedimentation rate was calculated as follows

$$m\ yr^{-1} = kg\ m^{-2}\ yr^{-1} / kg\ m^{-3}$$

and converted to a value reported as cm yr^{-1}. The daily TSS discharges (kg day^{-1}) reported approximately every 7 days between May, 1998, and March, 1999, were averaged and converted to an average TSS discharge (122.7 kg day^{-1}) and then to an annual TSS discharge (44,786 kg yr^{-1}). Annual sedimentation rates over the depositional area of the tidal channel were calculated as 0.2 cm yr^{-1}. Daily sedimentation rates (< 1 mm day^{-1}) were also calculated using a maximum daily TSS discharge of 749.8 kg day^{-1} reported on November 23, 1998. In addition, daily sedimentation rates were calculated using this TSS discharge value over a smaller depositional area (10 m^2).

APPENDIX I. Abridged report from Precision Identification (1998) concerning Bonsall Creek estuary vegetation mapping.

Species Composition

Imi - In addition to the species listed on the habitat map *Cuscuta salina* (salt-marsh dodder), *Spergularia marina* (salt marsh sandspurry), and *Atriplex patula* (saltweed) were present.

Iml - additional species included *Cuscuta salina* (salt- marsh dodder).

Habitat Types

There is a zone of vegetation which shows up distinctly on the air photos, usually between the polygons that fit the description of Imi and Iml. The zone is not adequately described by either Imi or Iml, either this transition type zone was classified as Iml in the earlier study, or it has developed since in response to sediment accretion. The *Distichlis spicata* (seashore saltgrass) could be invading the area previously occupied by *Salicornia virginica* (glasswort). I described this habitat based on the area that I ground-truthed, however the colour and texture distinctive of this zone were also present near the Chemanus River. I have assigned a new code Iml/mi to this polygon type. A description of this zone is provided below.

Iml/Imi - This habitat occurs in the mid intertidal, frequently between the Iml and Imi zones. It is characterized by a dense cover (70% to 95%) of *Salicornia virginica* (glasswort) and *Distichlis spicata* (seashore saltgrass) which are co-dominant. *Cuscuta salina* (salt marsh dodder) and *Glaux maritima* (sea milkwort) are present. This habitat was described from the southeast corner of the study area in Campbell et al. (1982) but appears to be present elsewhere as well.